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Article — Published Version Calculating the Environmental Benefit of Reuse Platforms

Circular Economy and Sustainability

Provided in Cooperation with: Springer Nature

Suggested Citation: Rückert, André; Balkute, Grita; Dornack, Christina (2024) : Calculating the Environmental Benefit of Reuse Platforms, Circular Economy and Sustainability, ISSN 2730-5988, Springer International Publishing, Cham, Vol. 4, Iss. 3, pp. 1913-1936, https://doi.org/10.1007/s43615-024-00360-y

This Version is available at: https://hdl.handle.net/10419/316981

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ORIGINAL PAPER



Calculating the Environmental Benefit of Reuse Platforms

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Received: 27 October 2022 / Accepted: 22 February 2024 / Published online: 4 April 2024 © The Author(s) 2024

Abstract

Reuse platforms are contributing to the circular economy by hosting or mediating unwanted products or materials until new users are found. This saves products from premature disposal on one hand, and avoids new products purchase on the other. Translating this resource efficiency and waste minimisation into GHG emission avoidance can support the relevance of reuse platforms in fostering a circular economy and promoting climate protection through resource preservation and potential GHG emission reductions. The authors present the analysis of existing reuse methodologies and point out incomplete considerations in terms of LCA modules and Corporate Carbon Footprint of reuse platforms [11]. This paper fills the gap in literature by formulating a holistic methodology for calculating benefits of reuse in terms of GHG emissions for the whole reuse sector and provides an application guide for 4 different types of reuse platforms. This new approach is then illustrated by applying it to a reuse enterprise Zündstoffe Materialvermittlung Dresden (ZUMADD) case study, for which data was gathered for 2 years under Dresden Future City Project (2019–2022). The results show that the project could save 13,301 kg of CO_2e emissions through mediating 6,213 kg of material for reuse.

Keywords Reuse of materials and products \cdot Resource preservation \cdot GHG emissions \cdot Circular economy \cdot Reuse platforms

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Introduction

In 2008 the European Waste Framework Directive (WFD) 2008/98/EC [1] was first published and with it the waste hierarchy in Article 4. Since then, waste prevention has been named as the most important goal in the EU and EU member states and their waste management systems (e.g. Circular Economy Act - Kreislaufwirtschaftsgesetz in Germany). One of the most important aspects in waste prevention, according to the Ellen MacArthur Foundation among reduction, recycling, rethinking, repairing and refusing, is the reuse of products and materials [2]. Stahel [3], among others (Bocken et al. [4], Castellani et al. [5], Fortuna et al. [6], Wilts et al. [7], Migliore et al. [8]), states that reuse is the key to implementing a circular economy and resource preservation.

As reuse is becoming an even more important solution to resource preservation, reuse platforms contribute to a circular economy by acting as redistribution mediators of various products and materials at their end-of-life. In doing so they support waste minimisation over waste treatment. Although waste prevention is a major goal in the waste hierarchy, there is still no universally valid methodology for calculating the environmental benefit of reuse. This article aims to fill this scientific gap in literature with a holistic methodology for evaluating the climate benefits of reuse platforms and applies it to a case study for an illustration. It shows how most of the reuse sector could apply this methodology and provides an application guide for 4 different types of reuse platforms (as broken down by Fortuna and Diyamandoglu [9]).

A reduction of greenhouse gases (GHG) in all areas of daily life is a crucial field of action in the fight against global warming, therefore the environmental impact category 'Global Warming Potential' (GWP) has been chosen as a reuse benefit measure for this methodology. It is an indicator most developed for public communication, commonly known as Carbon Footprint (CF), and is expressed in kg of CO_2 equivalents (kg CO_2e). Reuse footprint calculation can help support the existence and growth of reuse platforms by highlighting their relevance and promoting public interest in reuse (Ordonez et al. [10]).

To illustrate the lack of common methodology for reuse, the article provides a literature review of existing reuse methodologies and highlights differences in their approaches. The authors show an existing lack of consideration for the Corporate Carbon Footprint (CCF) of reuse platforms on one hand, and on the other, the consideration of avoided emissions of only one product's Life Cycle Assessment (LCA) phase. The authors, however, argue that the whole Product Carbon Footprint (PCF) is avoided through material reuse and visually show that if a used product replaces a new product purchase, not only the end-of-life-phase (EOL-phase), but also the production phase in the product life cycle is prevented (Balkute [11]). Furthermore, the authors go on to recommend that CCF of reuse platforms should be added to the environmental benefit of avoided emissions through material reuse, because although their CCF may be relatively small, product redistribution would not be possible without reuse platforms. Besides, to consider only the positive impact of reuse and dismiss essential emission-causing actions such as transportation and storage would be biassed. Furthermore, requiring reuse platforms to measure and manage their emissions creates an opportunity for the involved stakeholders to become more aware of their own emissions and so make more environmentally friendly decisions (especially important in regards to product redistribution distance). The importance of this is highlighted by Corporate Sustainability Reporting being legally required by EU law for large companies since 2023 (European Commission [12]).

Article 11 of the WFD the European Commission requests that member states shall take measures to promote reuse activities, notably by encouraging the establishment of and support for reuse and repair networks, the use of economic instruments, procurement criteria, quantitative objectives or other measures. In Germany the waste prevention strategy was first published in 2012 and redefined in 2020 [13]. The newly published version mentions a reuse enterprise (RE) *Bauteilbörse Bremen*, which is specialised in the mediation of used construction materials that vary from used windows to reclaimed ceramic tiles. *Bauteilbörse Bremen* is one of many projects in Germany enabling reuse of various materials on a regional level (Sect. 2.1 provides overview of reuse platforms). Among these projects is the *Zündstoffe Materialvermittlung Dresden (ZUMADD)* that started its activities in 2018.

ZUMADD is mainly focused on promoting the reuse of materials in the local arts and culture scene, including museums, theatres, local artists, but also in a broader context like small and medium local businesses, organised civil society and private persons. The flow of used materials through this material exchange initiative was measured as part of a case study undertaken by *TU Dresden Institute of Waste Management and Circular Economy*. The mass and the type of materials that came in and out of *ZUMADD's* storage facility was collected for 2 years during the Covid-19 Pandemic. Due to a change in opening hours and lockdowns, the collected data cannot be compared with a business-as-usual scenario. The aim of the case study was to collect data so that the environmental impact of this RE could be calculated and the waste minimisation in Dresden could be made visible. Important to mention is that the RE ZUMADD does not mediate products that need electricity during their use-phase. It is an important factor when evaluating the carbon footprint of a product, which also informs and limits the scope of this methodology to non-powered products only.

Materials are sometimes referred to as products in this paper because materials, which become component parts of other products, go through their own production process. For instance, materials such as fiberboard can be seen both as material and as a product. A product, because it needs to be produced out of timber, and a material because it can be used as a component in producing a table. An LCA is needed to determine PCF and the avoided emissions through product reuse. A fiberboard can get its own LCA just like a table can.

The following article first gives a brief introduction into the definition of reuse platforms, before going into the analyses and comparison of various case studies that were described in literature in the past (see Table 1). In the methodology section the authors describe the combination of product carbon footprint, calculated using reference materials, and the corporate carbon footprint. The combination of the two leads to the given results (see Sect. 4). The article ends with a discussion and interpretation of the calculated results for ZUMADD RE.

Literature Review

Reuse Platforms Overview

The authors' research has shown a strong presence of local platforms mediating secondhand consumer goods across Europe and only a handful of literature on the positive environmental impact of this sector, mainly covered by L. M. Fortuna [2016, 2017, 2018]. The largest number of reuse platform examples can be found under *rreuse.org*. RREUSE is an international network set out to empower, represent, and support the social and circular enterprise community in Europe as well as to ensure well-designed EU policies for reuse platforms. Some other smaller networks for reuse platforms include *reusedeutschland.org* and material-initiativen.org while *reloopplatform.org*, zerowasteeurope.eu, reflowproject. eu, upstreamsolutions.org and reuseportal.org are platforms set up for an even broader scope of reuse solutions and knowledge sharing.

There are few websites offering a tool for calculating CO_2e avoided emissions through reuse of products [14, 15; 16]. The calculators offer a simplistic user interface with a range of household products to choose from. After entering the number of the objects reused, the calculators provide different values such as avoided emissions, money saved, litres of water saved as well as, for instance, 4 equivalent comparisons. This user-friendly simplification is made for motivational purposes as it can give its users a vague idea of the positive impacts of reuse, but it doesn't state how exact it is. Provided CO_2e emission values per product seems to be based on avoided EOL-phase only, without transportation taken into consideration and not backed up by data sources. The presented calculators don't include any of the materials that enterprises such as the ZUMADD mediate, which highlights a knowledge gap for the described reuse sector recirculating materials in the local arts and culture scene as well as in a broader context like small and medium local businesses.

Article 3 of the WFD [2008/98/EC] defines reuse as 'any operation by which products or components that are not waste are used again for the same purpose for which they were conceived'. The definition for reuse applied in this paper is similar to the one stated by the European Commission, but also includes upcycling processes where materials were used for different purposes than before they came through the ZUMADD project. For example there were theatre floorings that were repurposed as walls for an indoor bouldering gym or packaging materials that were repurposed in a theatre production as clothing. The repurposing of materials in an upcycling process differs from the classic term recycling, as the material is not changed in its composition and is legally not considered waste material that has to get turned back into a resource for production processes. The processes needed to repurpose the materials (cutting, drilling, sewing etc.) in an upcycling project were not included in the described methodology as they were outside of the chosen system boundaries. The system boundaries only included the actions taken by the material exchange platform.

Types of Reuse Platforms

To understand the role of ZUMADD in the reuse process it is necessary to define the different actors in the reuse process and show differences between them. According to the definition of Fortuna and Diyamandoglu [9] the ZUMADD can be considered as a non-profit RE. Fortuna and Diyamandoglu define these REs as entities (operating as either non-profit or for-profit) that manage warehouses, outlets or thrift stores which serve as exchange locations for second-hand product donors and consumers. REs receive and/or collect unwanted used materials from donors. They sort, store and market these used goods, might provide delivery services to their customers and might additionally promote products online. The distinction between the two types or REs is as follows:

- Non-profit REs receive material donations from various stakeholders and mediate the material in exchange for a monetary donation.
- For-profit REs would include used-car dealers, antique stores or second-hand textile stores among other examples.

RE's main emission sources may include energy use in storage facilities and product transportation.

Besides the described RE, Fortuna and Diyamandoglu differentiate between three more types of reuse platforms which enable reuse of products. These are *material exchanges*, *online platforms* and *direct exchanges* as depicted in Fig. 1.

Material Exchanges (MEs) are defined as entities that facilitate direct exchange of products between Material Donors (MD) and Material Receivers (MR) through an online service, and without having a facility for intermediate storage. Material exchanges are mediating materials between businesses, individuals and organisations and are actively looking for potential end users, so that still valuable products are directly used again, and their premature disposal is avoided. RE might take in materials from ME as an intermediate party if an immediate MR is not found by the ME. One example for a ME is TRASH GALORE from Leipzig (trashgalore.de), facilitating material transfers in various cities across Germany. ME's main emission sources may include energy use in office facilities and product transportation.

Online Platforms (OPs) are digital tools that passively help the exchange of goods among users. The exchange can be either monetary or free and is arranged on platforms such as eBay, Kleinanzeigen, Quoka, Craigslist etc.. These platforms do not act as active brokers searching for MRs like MEs do, they act rather like digital material exchanges in a database form. The MRs contact the MDs directly through these platforms to facilitate the material exchange face to face. Online platforms can even operate on a global level, however



Fig. 1 Reuse platforms (adapted from [9])

the benefit of reuse becomes questionable because long distance redistribution emissions are likely to be higher than emissions avoided through product reuse. OP's main emission sources may be associated with the online domain and cloud storage as well as product transportation.

Direct Exchanges (DEs) between MDs and MRs happen without any help from an intermediate party. They can happen between acquainted or related individuals as well as between strangers when exchange happens during swap events such as flea markets. DEs can be categorised as opportunistic exchanges, because of their temporary and dynamic nature of no fixed location or opening times for exchange. DE's main emission sources would include product transportation.

Ability to quantify and qualify the environmental benefits that arise through reuse of products can provide various advantages. Environmental impact information can allow the involved stakeholders to make optimal environmental decisions for redistributing products for second life as well as motivate more stakeholders to use resources more efficiently and improve local resource circularity.

Related Case Studies and Methodologies

Several scientific case studies (Quack [17]; James [18]; Ludman & Vogt [19]) and methods (Castellani et al. [5], Fortuna & Diyamandoglu [9]) have attempted to calculate the GWP benefit achieved though reusing various non-powered products and materials in different product sectors. However, there are clear discrepancies among them as to how the GWP benefit should be calculated for reuse platforms, which showcases the necessity for one holistic approach. The presented methodology sets out to solve these discrepancies by evaluating methods found in literature and proposing an adapted methodology based on the evaluation. The following paragraphs describe relative literature which authors have used to make an informed evaluation.

Quack (2003)

The aim of the case study by Quack [17] was to determine the energy savings associated with the reuse of building components. Parallel to this, the reduction potential for CO₂e emissions was determined. To calculate the reduction potential, two scenarios with and without reuse were compared. The scenario "without reuse" included a whole lifecycle of a product (cradle to grave) and an additional production phase of a new product. The scenario "with reuse" considered a product's life cycle from cradle to dismantling. Quack added a refurbishment-phase and an additional use-phase to represent the second use of a product. The estimation was made that the second use-phase only had a 50% lifetime of the first use-phase. The emissions caused during the instalment of the product, during the use-phase and the transportation emissions were neglected, as the data was not available. In the end the two scenarios were compared to find out the benefit of product reuse.

James (2011)

"[The] methodology for quantifying the environmental and economic impacts of reuse" (James [18]) created by UK Waste and Resource Action Programme (WRAP) is based on

LCA and Cost Benefit Analysis (CBA) methodologies. It provides a framework for identifying the merits of reuse (100% direct reuse, 100% preparation for reuse) compared to alternative EOL-options (100% landfill, 100% recycling, 100% disposal). Environmental indicators considered include GHG emissions, energy demand and resource depletion. WRAP methodology guides to consider the whole life cycle of products, different used product displacement scenarios and rates as well as anticipated duration of the second life of a product. The methodology and excel tool so far have been tested in case studies on furniture, electrical equipment and clothing items. The use-phase of non-powered products is excluded as they are negligible and may lead to double counting, while the EOL-phase is attributed to reuse activity. The methodology recommends determining the maximum life time duration of a product and to collect referenced data for allocating the proportion, type and duration of a new product displacement with a used product.

Castellani, Sala, Mirabella (2015)

Castellani et al. [5] developed a standardised procedure to quantify avoided impacts through reuse of products. It involves grouping various products into categories and choosing a representative product for them; creating an inventory with average characteristics for each representative product; calculating average avoided impacts based on predefined functional units, the inventory and LCA data of representative products. In case of complete substitution, Castellani states that 100% of the impact of extracting resources from the environment, manufacturing, and transporting a new product is avoided if a second-hand product is purchased instead of a new product. It must be noted here that EOL-phase is not considered as an avoided impact in this methodology. The second part of the procedure involves inventory data collection over 1 year and calculation of avoided impacts. To account for the fact that 100% new product substitution is not always the case when buying second-hand products ([18, 20]), Castellani has found the rate of substitution for the case study in Italy by direct survey of customers, which is deducted from total avoided impacts. A sofa, a sideboard, a T-shirt, a sweater, and a drinking glass were taken as reference products in this case study.

Fortuna, Diyamandoglu (2017)

Fortuna & Diyamandoglu [9] created a framework that helps to identify the best management strategies for reducing disposal and increasing reusable products recovery. The framework incorporates various reuse platforms into a traditional solid waste management system as additional internal steps that take place before reused products reach the EOL-phase. The framework includes all processes and flows of products that take place between various donors and recipients, as well as the potential disposal routes (recycling, landfill, incineration). The mass flow of products and the GHG emissions from the system being modelled as a whole are used as two indicators for the assessment of the framework. Waste diversion through reuse represents mass flow constraints that contribute to GHG emissions reduction and material recovery. The total GHG emissions minimization is a function of the transfer coefficients, mass entering the system, emission factors, and transport distance. The framework was applied to material flow of second-hand clothing as a case study.

Ludmann, Vogt (2019)

The case study by Ludman & Vogt [19] was performed for the senate department of Berlin city to estimate the environmental impact of reuse and preparation for reuse for three types of second-hand materials: wood furniture, laptops and shoes. It was estimated that the preparation for reuse and reuse afterwards causes a lifetime extension of the product. Consequently, the saved emissions depend on the average lifetime of a product and the years that a product is further used through reuse. For instance, a table has an average lifetime of 15 years. After 5 years the table goes into reuse, which causes an emission savings of 66% because it is used for 10 more years and substitutes the primary production of a new table accordingly. Transport was included into the calculation. The EOL-phase was not included in the calculation as the products are not yet defined as waste and therefore the system boundary didn't include the waste management system in place.

The following Table 1 shows a comparison of the chosen case studies.

Clearly the results of reuse benefits vary based on the method and system boundaries used as well as the type of products examined. There's a strong correlation between PCF of a product, the transportation distance for reuse, the alternative disposal scenario emissions and the emissions caused at the intermediate storage facility. For instance, the further the distance for used material transfer and the more energy used to run the intermediate storage facility, the more additional emissions reuse is causing. Methodologies examined in literature review mostly attribute additional reuse processes to expanded PCF scope of each product rather than to the reuse platform that enables these processes. This works well when only several specific products are being evaluated but becomes very complex for reuse platforms with significant diversity of materials such as ZUMADD.

Other studies, like Castellani et al. (2015), neglect corporate carbon footprint on the basis of insignificant energy use in the storage facility. However, according to the GHG Protocol and the scopes it provides, organisations have many diverse emission causing activities that enable their operations, so evaluation of avoided emissions without considering created emissions would give one-sided evaluation. But more importantly it would make it impossible for REs to show with how little effort they can produce immense carbon savings and declare their relevance in society and the local waste management system [10]. Therefore, the authors recommend accounting for emissions that are caused while facilitating reuse (through CCF) for an unbiased evaluation of reuse impacts. Although additional indirect activities that fall into Scope 3 are officially optional according to GHG Protocol, the authors recommend reuse platforms to consider them.

Studies like Castellani et al. (2015) also do not consider EOL-phase as avoided impacts. In their literature review, Fortuna & Diyamandoglu also observe that the majority of studies on the environmental benefits of reuse mainly incorporate emissions from avoided production in their frameworks and do not consider EOL-phase. The methodology in this paper shows how reuse substituting new products can result in EOL-emission avoidance when high substitution rate is considered.

Author (Year)	Title	Method	Functional unit	System boundary	Impact categories considered	Substitu- tion rate	Note
Quack (2003)	Determina- tion of the energy saving potentials and CO_2 reduction potentials that can be realised through the reuse of used components	Compari- son of two scenarios	Provision of refer- ence ma- terials and individual determina- tion of the unit (1 m ² or 1 kg)	Cradle to Grave vs. Cradle to Reuse	Primary energy demand and GWP	50 %	Balance sheet frame- work of the two scenarios is not consistent
James (2011)	A Method- ology for quantifying the environmental and economic impacts of reuse	Comparison of several scenarios	1 Mg of mediated material in different categories	Cradle to Grave vs. Cradle to Reuse to Grave	Primary energy demand, GWP, resource consump- tion, jobs and costs	Indi- vidual substitu- tion rates depend- ing on theo- retically maximum possible time of use and time already used	Reuse scc- nario of a product compared with different EOL- scenarios
Castel- lani, Sala, Mira- bella (2015)	Beyond the throwaway society: A life cycle-based as- sessment of the environmental benefit of reuse	LCA	l kg of brokered products from 5 different product categories	Cradle to Reuse	All impact categories according to ILCD 2011	Indi- vidual substitu- tion rate, which was deter- mined by survey	Individual transport emissions were neglected
For- tuna, Diya- man- doglu (2017)	Optimization of greenhouse gas emissions in second-hand consumer product recovery through reuse platforms	Combination of a material flow model with emis- sion factors and transport data	Individual mass of a material moving in the system	Use to Grave	GWP	Mass- based substitu- tion rate	Frame- work con- ditions are discussed, but only theo- retically applied to textile market

Table 1 C	Comparison	of case	studies and	l overview	of used	methods
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Author (Year)	Title	Method	Functional unit	System boundary	Impact categories considered	Substitu- tion rate	Note
Lud- mann, Vogt (2019)	Preparation for reuse - orient- ing life cycle assessment for three second- hand goods Within the framework of the material flow, climate gas and environmental balance for the year 2018 for the state of Berlin	Calculation of emission savings through preparation for reuse and ac- complished product life extension	Provision of three reference materi- als and individual determina- tion of the unit	Cradle to Reuse	GWP always and individual impact cat- egories per product	Indi- vidual substitu- tion rates depend- ing on theo- retically maximum possible time of use and time already used	Potential calcula- tion of individual savings based on three example products, including trans- port in use-phase

Table 1 (continued)

Material and Method

Based on literature review and ZUMADD case study evaluation, it is concluded and recommended, that the following aspects and system boundaries should be considered when calculating the environmental impact of reuse through a chosen reuse platform:

Method: Avoided PCF plus created CCF

- PCF: Product carbon footprint emissions not emitted through used product replacing new product (negative kg CO₂e)
- CCF: additional corporate carbon footprint emissions created while making used product available to new users (positive kg CO₂e)

Functional unit: Mass of material passed on for reuse in kg over a period of time (a year or months)

PCF system boundary: Cradle to grave with use-phase as zero emissions for non-powered products and materials

CCF system boundary: GHG protocol with preselected most relevant Scopes 1, 2 and 3 for reuse platforms (see table 2)

Impact category considered: Global Warming Potential described as fossil carbon emissions

Substitution rate: 100 %

Notes: The higher the substitution rate the more positive climate impact as it means reduced consumption of resources, while no substitution means additional consumption [26]. Reuse platforms might use individual substitution rates if known through surveys for a more precise reuse impact value (see section 3.2.4).

GHG Protocol Corporate Carbon Footprint		Reuse Enterprise	Material Exchange	Online Platforms	Direct Exchange
Scope 1 Direct Emissions	1.1 Stationary Combus- tion (e.g. natural gas, hot water heater, oil burning boiler)	Recommended, if applicable	Recommended, if applicable	Recom- mended, if applicable	Recom- mended, if applicable
	1.2 Mobile Source Emis- sions i.e. material trans- portation by organisation owned vehicles	Recommended, if applicable	Recommended, if applicable	NA	Recom- mended, if applicable
Scope 2 Indirect Emissions	2.1 Purchases of Electricity	Recommended, high importance	Recommended, high importance	Recom- mended, high importance	Recom- mended, if applicable
Scope 3 Indirect Emission	3.1 Employee Business Travel	Recommended, if applicable	Recommended	Recom- mended, if applicable	NA
(Optional reporting)	3.2 Employee Commuting	Recommended, if applicable	Recommended, if applicable	Recom- mended, if applicable	NA
	3.3 Product Transport by vehicles not owned by organisation i.e. hired transport, estimated trans- portation distance by User 1 and User 2.	Estimations for donor & receiver travel	Recommended, if applicable	Recom- mended, if applicable	Recom- mended, if applicable
	3.4 Waste (transportation and treatment of waste)	Recommended, if applicable	Recommended, if applicable	Recom- mended, if applicable	Recom- mended, if applicable
	3.5 Purchased Offsets	Recommended, if applicable	Recommended, if applicable	Recom- mended, if applicable	Recom- mended, if applicable

 Table 2
 Guidance for the 4 types of reuse platforms on corporate emission sources based on GHG Protocol

Scope and System Boundaries

Each material and product goes through life stages of production, use and disposal (endof-life). Figure 2 depicts which life phases and their associated emissions are avoided with reuse. The CCF (blue fields) and PCF (yellow and red fields) depicted in Fig. 2b, show that through substitution of a new product with a used one (as it travels from User 1 to User 2), both the production phase and the EOL-phase of a product (depicted in red) are avoided. More specifically, if a purchase of a used Product P1 replaces a purchase of a new Product P2, a new product (P2) presumably doesn't need to be produced, and if it's not produced, there is no EOL-phase of it to consider. However, additional emissions are created as the transfer of a used product from one user to another happens through a reuse platform (blue field, CCF). These additional CCF emissions of a reuse platform should be balanced against the avoided PCF emissions (red fields).

The reason for allocating additional emissions of transportation to CCF and not PCF is due to high diversity and complexity of products that REs tend to deal with. Allocating the transport emissions to materials of high diversity is difficult. Unlike in architecture and building industry, materials and products do not come with passports that show specific information about them and the processes they go through.



Fig. 2 a Business-as-usual scenario from Product (P1 & P2) perspectives: each product goes linearly through life cycle stages of "Production", "Use" and "End-of-life". Each creative practitioner (User 1, 2, etc.) acquires new material as needed, which must be produced new and is disposed of when no longer needed. **b** Product life pathway modification with reuse platform (RE/ME/OP/DE) intervention. Reuse platform enables the transfer of a Product P1, which displaces the production and disposal of an alternative new Product P2. Such further use of a Product P1 avoids premature disposal by User 1 as well as new production for User 2. DE mostly doesn't involve an infrastructure for storage but involves transport

The ZUMADD case study has shown that material inputs and outputs vary significantly in the daily business of a RE. Materials most often arrive mixed in one delivery, stay different lengths of time in the storage facility and leave in a diverse material mix. Due to this complexity, precise allocation of partial transportation and storage emissions to each product is not feasible, especially in this specific case study setup. However, allocation of reuse platform CCF over a period of time to the material flow PCF over the same period of time is feasible and recommended for a balanced impact evaluation of reuse. The CCF should in this case include actions of the reuse platform only. Short list of most relevant emission sources may include transportation, heating and electricity use. However, each organisation is individual and should use the provided guide (see Table 2) to identify their emission sources and define their scope. The storage facility in this case study was unheated.

If, like in the case of ZUMADD, the materials being reused do not need electricity in their use-phase, they do not produce use-phase emissions. In such a case, the calculation of the reuse impact involves production- and EOL-phase emissions. These emissions, as illustrated in Fig. 2, are avoided emissions, meaning they are carbon negative and can be understood as climate positive. In case the use-phase of a product requires electricity, the emissions need to be considered, which is a calculation not performed in this paper. In this case the environmental benefit of reuse cannot be guaranteed as new products might be more energy efficient.

A RE acts as an enabler for reuse by offering storage for materials that most likely would have otherwise been disposed of. Some REs actively gather used materials while others get them delivered. In the case of product delivery by other parties, theoretically that party should receive both the credit for not disposing and the footprint of additional emissions for transportation. Although theoretically the credit for taking circular action belongs to MDs and MRs (User 1 and User 2), their ability to mobilise secondary material flow and arrange

the gap that allows the supply a

DE is limited without RE, ME or OP. Reuse platforms fill the gap that allows the supply and demand of secondary products to meet. Especially REs and MEs are in a beneficial position to record and evaluate reuse activity for a particular locality. Therefore, authors recommend, the credit for emission avoidance through reuse should be communicated neutrally as a climate benefit that was achieved in a certain geography, acknowledging the participation of all three parties. If a reuse platform would like to claim the credit, it could let material donors and receivers sign a disclaimer which states that by giving or taking material they waive the right to claim the credit and give the right to the enterprise to calculate the resulting carbon emission.

Based on Figs. 2b and 3 shows in more detail how the system boundaries can be applied to any of the 4 reuse platforms for calculating the impacts of reuse. The scope, framed in a flow diagram, includes both the relevant LCA modules of PCF (yellow and red fields) and the additional processes enabling material transfer for reuse allocated to CCF (blue fields and arrow lines). Depicted in red fields are the avoided impacts of production module and EOL-module when enabled through reuse and perfect substitution of a new product with a used product. Preselected most relevant scopes of CCF to be considered are included in Table 2. This paper shows an example through REs, as ZUMADD fits its definition.

Further aspects influencing the calculation include material diversity (Sect. 3.2.1), data source and quality (Sect. 3.2.2), reference materials (Sect. 3.2.3) and the chosen substitution rate (Sect. 3.2.4).

Product Carbon Footprint Calculation Guidance

Material Categorisation

Materials in reuse platforms tend to have a high diversity of types and shapes, therefore a system should be implemented in the reuse facility or online platform system to categorize the materials according to their main material type [6]. In the case study of ZUMADD the



Fig. 3 Scopes and modules included into the calculation of the reuse benefit (own research). A single product's path from first use to second use (yellow fields) through reuse platforms (blue fields) and accordingly avoided LCA modules (red fields)

material categories were adapted to the categories used in waste sorting processes, as this task also deals with a heterogeneous system that must be categorized. The project team formed two levels of granularity. The main category at level 1 has higher granularity. Each material category at level 1 has several material subcategories at level 2, that have a lower level of granularity, are more specific and better fitting to the created reference materials (see Table 3). The "Guideline for Uniform Waste Analysis in Saxony" [21] served as a model for the material categories but was adapted accordingly to the needs of the project team and the materials that were received. Other types of reuse platforms should do their own categorisation based on their typical material mixes.

Data Source

Та lev

The data source used for the calculations has a big impact on the result of the environmental benefit of a reuse platform. Several database systems were tested for the case study. While there are few publicly available open-source databases that list CO₂e data on materials and products free of charge, Ökobaudat and IDEMAT proved to have the best properties concerning the aspects mentioned for the case study.

Ökobaudat database provided by the Federal Ministry for Housing, Urban Development and Building in Germany [22] provides more than 1,400 datasets for building products. IDEMAT database provided by ecocostvalue.com [23], a spinoff by the Delft University of Technology, is also a constantly growing database which is reviewed and adapted regularly. Both databases provide Life Cycle Impact Assessment (LCIA) datasets for specific products, materials and processes. The difference between the two is that the Ökobaudat

ble 3 Used material category	Material category level 1	Material category level 2
/els	Compound Materials	Paper-Plastics Compounds Plastics-Metal Compounds Metal-Glass Compounds
	Glass	Flat Glass Moulded Glass Wool
	Metals	Ferrous metals Non-ferrous metals
	Minerals (not glass)	Ceramics/Porcelain/ Stoneware/Tiles
	Paper, Cardboard and Carton	Paper (poster, flyer, news- paper, wallpaper) Cardboard and Carton
	Plastics	Extruded Calendered Foamed Blow moulded Acrylic Elastomer
	Textiles	Carpets Yard Goods (cotton, jute) Synthetic Materials
	Wood	Wooden beams and battens Wood panel material
	Natural materials (not Wood)	Wool Leather

database provides data about specific products and is dependent on the producer of the product to give out information about the impacts in the different product life cycle stages (see Table 4). The EPDs in the Ökobaudat platform also include more environmental impacts that are addressed in a LCA according to DIN EN ISO 14044. The IDEMAT database, on the other hand, provides data for life-cycle stages, not modules, of various materials and processes. Using a streamlined LCA approach, the reference materials were designed with IDEMAT material and process data to best fit the level 2 material categories and to represent similar life cycle modules (A, C, D) like the Ökobaudat datasets. All sources for the data are named in the databases. The IDEMAT database is also accessible through a free to download app [24]. Both databases are DIN EN 15804+A2 compliant [25].

Reference Materials

For each material category in level 2 (see Table 3) a reference material was created out of the datasets provided by Ökobaudat and IDEMAT database. Reference materials were created to best fit the chosen level 2 material categories through a so-called "Fast Track LCA" or streamlined LCA approach. They were based on the two databases or were built by combining data for material processes and EOL-phase if already combined data was not available. The following formulas show the used emission factors.

$$E_{n_{moduleX}} = \frac{E_{n1_{moduleX}} + E_{n2_{moduleX}} + E_{n3_{moduleX}} + E_{ni_{moduleX}}}{N}$$

Building Life Cycle Information						
Product Life	Module	Module	Product Life Stage Module			
Stage	Letter	Nr.	Name			
Production	А	A1	Raw material supply			
		A2	Transport			
		A3	Manufacturing			
Construction	А	A4	Transport			
		A5	Construction - Installation			
			process			
Use	В	B1	Use; installed products			
		B2	Maintenace			
		B3	Repair			
		B4	Replacement			
		B5	Refurbishment			
		B6	Optional energy use			
		B7	Optional water use			
End-of-life	С	C1	Deconstruction			
		C2	Transport			
		C3	Waste processing for reuse,			
			recovery or/and recycling			
		C4	Disposal			
Additional information	ation outsic	le the syste	em boundary			
Product Life Stage		Module	Product Life Stage Module			
		Letter	Name			
Potential benefits a	and loads	D	Reuse-, recovery-,			
			recyling-potential			

 Table 4
 Life-cycle stages according to DIN EN 15804+A2 that

 are used to produce Environmental Product Declarations for
 products and Materials and data

 for IDEMAT database
 Declarations

 $E_{n_{moduleX}}$ = individual average emission factor for created reference material during the life cycle stage (A, C or D)

 $E_{ni_{module X}}$ = specific emission factor for module X based on chosen dataset.

N=amount of used reference emission factors.

In this paper the authors solely focused on the fossil emissions that were depicted in the datasets provided, as the biogenic carbon balance is zero during an LCA. The GWP-luluc that accounts for greenhouse gas emissions and bonds that arise in connection with changes in the specified carbon stock as a result of land use and land use change was neglected due to its insignificance in comparison to the fossil emissions.

The mass flows of each product category were recorded during the project.

 $m_{i_{out}}$ = individual mass flows of mediated material

The following mathematical equations show the factors used to calculate the average product carbon footprints for each material category at level 2 (see Table 3) based on DIN EN 15804+A2 in combination with the amount of reused material mediated by the reuse platform in a certain time frame. The involved life-cycle stages and the accompanying modules A, C and D are shown in Table 4.

$$e_{moduleA} = \sum_{i=1}^{n} m_{i_{out}} * E_{i_{moduleA}}$$

 $e_{moduleA}$ = total saved CO₂e emissions through avoided production summed up over all material categories at level 2

$$e_{moduleC} = \sum_{i=1}^{n} m_{i_{out}} * E_{i_{moduleC}}$$

 $e_{moduleC}$ = total saved CO₂e emissions through avoided EOL-phase summed up over all material categories at level 2 without benefits through incineration or recycling

$$e_{moduleD} = \sum_{i=1}^{n} m_{i_{out}} * E_{i_{moduleD}}$$

 $e_{moduleD}$ = total avoided CO₂e credits during EOL-phase summed up over all material categories at level 2 due to incineration with electricity and heat production or due to recycling and savings of primary materials

$$e_{total} = \sum_{i=1}^{n} e_{moduleA} + e_{moduleC}$$

 e_{total} = total avoided CO₂e emissions without the use-phase over the lifecycle of the mediated products summed up over all material categories at level 2.

In the case of non-powered product transfer for reuse, modules A1, A2, A3 are recommended to consider when calculating avoided impacts of production. Modules C2, C3 and C4 are recommended when calculating avoided impacts of EOL-phase. Module D is considered to be out of the system boundaries of the EPDs and has to be accounted for individually. It should not be summed up with the other modules, as it would account for double counting secondary material inputs that are already included in Modules A1-A3. Whether a product creates potential benefits in its EOL-phase depends on three factors: its heating value, the waste management system in which the material would have been disposed into (thermal treatment with energy recovery) and the amount of material that would have gone into a recycling system if the material was to be recycled.

Furthermore, the modules A4, A5 and C1 were not considered in this case study as most EPDs don't provide data for these modules. For the Module C2 an average transport emission was estimated out of the data that was provided in the reference datasets. A list of the reference emission datasets can be found in the supplementary material.

Displacement or Lifetime Extension Approach

The displacement or substitution rate (hereafter substitution rate) describes how much the purchase of a used item replaces the purchase of a new item. The rate of substitution can vary from partial to a full 1:1 ratio, also called perfect substitution. Different approaches can be found in literature to estimate the substitution rate or lifetime extension of a product.

James [18] suggests that referenced data should be used to quantify the proportion of a reused product, which can displace a new item, reused item or nothing at all (meaning it's an additional purchase). Cooper & Gutowski [26] argue that to calculate the benefit of a reuse and to translate this savings into global reduction in energy use or emissions, a reused product has to displace the sale of a new product made from primary material. James, Fortuna and Cooper & Gutowski all state that the substitution rate can be estimated through behavioural tests and surveys among the users of secondary material or market data and analytical methods. The substitution rate derived from behavioural tests and surveys never turns out to have a 1:1 displacement (Ovchinnikov [27]; Ovchinnikov et al. [28]; Guide and Li [29]; Farrant et al. [30]).

Thomas [26] states that one of the few scenarios that would result in perfect substitution is the reuse of valuable materials that would otherwise be thrown away or left unused in storage. In this case study it was estimated that a reused material replaces a new material by 100%, as ZUMADD mostly deals with component materials that have been deconstructed for storage or disposal i.e. in the event and culture sector. If the substitution rate is known, the correct percentage should be deducted from the total results which first have to be calculated as if perfect substitution has taken place anyways.

Corporate Carbon Footprint Calculation Guidance

As previously explained, the corporate emissions that enable the infrastructure for, organisation and the transfer of products for reuse should be accounted for and allocated to CCF. A short list of preselected most relevant emission sources for each type of reuse platform are depicted in Table 2. The additional (from PCF perspective) activity of product transportation for reuse is recorded here, rather than allocated to each product's expanded PCF scope. The emissions of material transportation for reuse by the reuse platform with vehicles that the platform owns, belongs in Scope 1.2. If the reuse platform rents vehicles to transport the material or transportation is done by User 1 and User 2, then the emissions of these scenarios must be reported in Scope 3.3. When the information for User 1 and User 2 transportation distance and vehicle type is unknown, an average value should be estimated per delivery and pick up scenario.

This table is based on the *GHG Protocol Corporate Accounting and Reporting Standard* (*GHG Protocol*), which can be referred to for detailed explanation of emission sources. '*GHG Inventory Development Process and Guidance*' is a simplified guide based on GHG Protocol that's adapted to small organisations, which is recommended for small scale reuse platforms. It has been developed by EPA Centre for Corporate Climate Leadership [32] and provides non-expert friendly guidance (available at: https://www.epa.gov/climateleadership/ghg-inventory-development-process-and-guidance).

A reuse platform can identify its type (RE, ME, OP or DE) according to the definitions provided in Sect. 2.2 and apply the fitting guidance from Table 2 accordingly. For the instance of the ZUMADD case study, the guidance for a "Reuse Enterprise" applies and is presented here.

Results

The following section shows the results for the product carbon footprint, the corporate carbon footprint and the combination of the two over the period of two years. The product carbon footprint being a combination of the product mass mediated and specific CO_2e emission factors for each material category, while the corporate carbon footprint is based mainly on energy used in the corporate facility and the distance of material transportation combined with relevant emission factors.

Product Carbon Footprint

The storage facility of the ZUMADD project was monitored over two years. In these two years there were 189 opening days with 282 individual material inputs and 564 material outputs (always considering the material output category, not the number of material receivers involved). Figure 4 shows the results of the input-output analysis. A total of 6,213 kg of material were donated to the storage facility during the monitoring period and a total of 3,132 kg of material has left it, which leads to the turnover rate of 50.4%. The highest turnover rate was achieved in the category "Wood", in which 97% of the incoming material reached User 2. The lowest turnover rate was found in categories "Compound Materials" (13.8%) and "Minerals (no Glass)" (13.9%).

The high turnover in the category "Wood" can be explained with increasing prices for primary wood during the project time, which increased the demand for cheaper wood from secondary sources. Also, the universal application of wood as a construction material favoured the turnover for this material.

Figure 5 shows the calculated emissions for each material category at level 1, which is the result of summed-up material emissions of each subcategory at level 2. The highest avoided emissions can be seen in textile products (that have very energy intensive production), the natural materials (which involve breeding of animals for leather production with a high environmental impact) and the compound materials (where production of plastics, metals and glass also heavily influence the calculation of avoided emissions).



Fig. 4 Results of the Input-Output Analysis of the RE. Highest turnover rate in the category "Wood" (98.8%), lowest in "Minerals" (13.8%) and "Compound Materials" (13.9%)



Fig. 5 Avoided emissions of production- and EOL-phase modules and avoided benefits and loads due to reuse during the project

However, although production processes can be emission intense, the highest emissions are found in EOL-phase of products that are based on fossil fuels. The loads in the EOL-phase are depicted by the released emissions in module C. Inside the system boundaries of the LCA, the biogenic carbon emission is zero due to the binding of carbon in module A and release of it in module C. For this reason, the system boundaries of the case study were set to consider fossil emissions and the provided biogenic carbon in the datasets were disregarded. The case study results show that the highest impact products for reuse are those that are based on fossil carbon as they release primary CO_2e emissions in module C or require intense fossil energy use in module A.

In the linear product use scenario Module D depicts the potential benefits gained during EOL-phase. These could be processes such as generating energy through material waste incineration. Therefore, it can depict the potential benefit of the scenario in which the product had been disposed of instead of reused. It can also give an insight if a product is more

suited for reuse or for its embedded energy recovery or raw material recovery potential in the EOL-phase. However, given proposed methodology in this paper, even with high benefits shown in Module D, reuse is still more efficient because both production and EOL-phases are avoided with high rates of substitution in the reuse scenario. This is evident in results shown in Fig. 6 discussed at the end of the chapter. Furthermore, even after several uses, products still reach the EOL-phase where appropriate possible benefits can be regained. As already mentioned in Sect. 3.2.3, module D is not included into calculations due to potential double counting but is displayed in the results separately for reasons of comparability.

Finally, Fig. 6 combines avoided emissions of all product categories under each life cycle module (A, C and D). The third column in the figure sums up modules A and C to show the total avoided emissions through ZUMADD enabling product reuse over two year period. The fourth column through the total sum of module D shows the total potential benefits and loads of the scenario, had this amount of material been disposed of prematurely, whose absolute amount is 6.3 times less than the total avoided emissions achieved through reuse that replaces new materials with used ones.

Corporate Carbon Footprint

The RE ZUMADD used 35 kWh electricity in the two year case study period. The only electricity consuming objects were light bulbs and a weighing scale during the opening hours. According to the regional electricity mix in Dresden, this amounts to emissions of 14 kg CO₂e. As the participating stakeholders were not asked which means of transport, they used to bring the material to the storage facility, a scenario was created where 50% of the individual material inputs or outputs above 5 kg were transported with a diesel car that uses 7 l of diesel over a course of 100 km and emits 2.65 kg CO₂e accordingly. The average transport route was estimated to be 10 km. Scope 1 emissions were not recorded during the monitoring period. The same applies for the various Scope 3 emissions apart from the transport of materials done by material donors and receivers.



Fig. 6 Total aggregated avoided (Av.) emissions during production-phase and EOL-phase and avoided "Benefits and Loads" due to reuse

Table 5 Caused CO2e emissions in the RE during the monitoring period	Cooperate emission type	Emission amount in kg CO ₂ e	
	Scope 1 emissions	0 kg	
	Scope 2 emissions (from electricity purchase)	14 kg	
	Scope 3 (3.3) emissions from transport Input	112 kg	
	Scope 3 (3.3) emissions from transport Output	124 kg	
	Total emissions	251 kg	

The emissions caused through the ZUMADD are shown in Table 5. With 189 opening days, the material transportation, storage and mediation process the total amounted to 251 kg CO_2e , which breaks down to 1.33 kg CO_2e per opening day.

The total of 6,213 kg of secondary materials could be mediated through the RE ZUMADD, which potentially avoided 13,301 kg CO_2e emissions, of which 85.72% were generated by avoiding a production phase and 14.28% through the avoidance of the EOL-phase. The ZUMADD caused 251 kg CO_2e emissions during the monitoring period. The CO_2e balance of the RE could be summed up to 13,050 kg CO_2e potential avoidance.

The CCF CO_2e emissions of the case study RE are very low compared to the summedup emissions of the PCF, but they are not negligible, because the CCF substantially highlights the positive impact of the RE. The case study results clearly show the positive impact of reuse platforms operating locally, since significantly more environmental (and social) value is added than additional emission output is created.

Discussion

This paper calculates the contribution to climate protection that a reuse platform e.g. a RE, produces through its actions based on LCA data complying with DIN EN 15804+A2. The whole concept is highly theoretical, as it tries to measure the benefits of waste avoidance through a product that was not produced and not bought due to the alternative purchase of a second-hand material instead, which consequently saves resources and avoids additional waste. As theoretical as the discussion whether reusing products causes an avoidance of production, is the question of substitution of new products with second-hand products. As stated by other authors, the substitution rate could vary depending on the material reused. Furthermore, rebound effects (which are not part of this paper, but are mentioned in literature about reuse) are possible, through which positive effects of reusing materials could be negated. A possibility of rebound effect must be acknowledged. This means that reuse platforms can also enable extra purchases (or hoarding behaviour) which may lead to increased consumption [26]. This should be attempted to avoid by only selling materials to those who already have a specific need and use for the material. This information could be filtered through communication with MR.

The calculated avoided potential benefits and loads through module D are based on different EOL-scenarios, so the results in the EPDs are highly dependent on the waste management system in which the disposed material ends up. Additionally, as the data is geographically dependent, it can lead to misinterpretation of module D emission data because of the differences in waste management systems among different localities. Depending on how an LCA is conducted, its results could show that in societies where energy is produced from fossil fuels, a thermal treatment of biogenic materials like wood could have a higher benefit than recycling it or even reusing it. This would neglect the sequestration effect that reusing wood and other biogenic materials have on the CO_2e emission balance and, therefore, climate protection. Furthermore, the data provided by the chosen databases lacks more detailed information, especially concerning emissions in the modules A4, A5 and C1, which could be improved in the future. Likewise, the streamlined LCA data used for this paper differs to the datasets used for the production of the reference materials, because different databases were used for the production of life cycle inventories.

The results of the calculations presented here are also highly dependent on the chosen reference materials. The reference materials used in this paper were chosen to fit the materials mediated in the case study as close as possible. Creators of reuse benefit analyses should choose their reference materials according to their needs.

With the improvement of publicly available LCA data for products and materials containing biogenic carbon (according to DIN EN 15804+A2), it would also be possible for reuse platforms to calculate the avoided emission through sequestration of biogenic carbon in addition to avoiding the emission of fossil carbon, as shown in this paper. But to do so, it is necessary for the reuse platforms to understand the data provided in the product databases if they want to do it themselves. The positive effect of having the CO_2e emissions data available publicly could be negated due to the complexity of its presentation, which may create obstacles of reuse platforms in terms of interpretation and correct application when attempting to calculate their reuse benefits.

The emissions caused by the RE in the case study might be small but should not be neglected. The energy use in the storage facility is highly dependent on the state of the building (age, isolation, renovation). Furthermore, when reuse platforms work over long distances and transport materials on a regional or supra-regional level, the benefits of reuse could be negated due to the means of transport. By tracking and calculating their CCF, these platforms can ensure that their actions don't negate the positive effects of reuse. One aspect that this paper did not consider is the ongoing process of digitisation and digitalisation of data concerning materials and products. If reuse platforms operate a website, climate relevant emissions are caused through the hosting of the website and the user traffic on it. How severe these emissions are, depends on the local energy mix.

Altogether, an improvement of standardisation for the calculation of LCA data, clear rules for its usage and more availability of publicly available life cycle inventories could support the endeavour of making the benefit of reuse better comparable on a material and product basis and reduce the margin of error in the results.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43615-024-00360-y.

Acknowledgements Not applicable.

Author Contributions André Rückert and Christina Dornack contributed to the study conception and design. Material preparation, data collection and analysis were performed by André Rückert. The first draft of the manuscript was written by André Rückert and Grita Balkute. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The research leading to these results received funding from German Ministry of Education and Research (BMBF) under Grant Agreement No [13ZS0057C]. Open Access funding enabled and organized by Projekt DEAL.

Data Availability Not applicable.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests Not applicable.

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