DOI: 10.1111/jiec.13240

METHODS, TOOLS, DATA, AND SOFTWARE

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Functionality-based life cycle assessment framework

An information and communication technologies (ICT) product case study

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Editor Managing Review: Vered Blass

Funding information
This work was supported by the Sykes Family Fellowship, Charles & Roberta Katz Family Fellowship, McGee and Levorsen Research Grant, and the Emmett Interdisciplinary Program in Environment and Resources (E-IPER) Summer Grant

Abstract

Life cycle assessment (LCA) has been widely applied to assessing the environmental impacts of information and communication technologies (ICT) products throughout their lifetime. Building upon LCA methodology, this study proposes a user-oriented, functionality-based LCA (FLCA) framework that evaluates the environmental impact of multifunctional ICT products such as smartphones. Incorporating the quality function deployment and LCA literature, we develop an approach that highlights the linkages among user behavior, product functionalities, and product environmental footprints. We use matrix algebra to outline a computational method and a streamlined process to operationalize such analysis. FLCA analyzes the impact of materials in the context of how they are used. To illustrate the concept with a simple example, our first case study calculates the manufacturing GHG emissions of a well-known multifunctional product, a Swiss Army knife. In the second case study, we estimate the functionality-based GHG emissions of a hypothetical smartphone. We consider various scopes of impact, including at the levels of device, infrastructure, and supply chains. Extending from LCA methods, FLCA moves away from a general understanding of functionality to a more granular perspective to accommodate the complexity in modern ICT products. Our study advances a user-oriented perspective to understand product sustainability impacts. Additionally, it offers a method to provide empirical evidence of the "hidden" impacts of industrial products during consumption, enabling more precise linkage of the production-consumption relationship through LCA toward better design to uncover and address users' needs.

KEYWORDS
consumer behavior, electronics, industrial ecology, information and communication technologies, life cycle assessment, product design

1 | INTRODUCTION

The information and communication technologies (ICT) industry is one of the fastest growing industries globally (Farhadi et al., 2012). ICT products such as smartphones and computers are ubiquitous: As of 2017, there were more than 7 billion cell phone subscribers, as many as the number of people on earth and approximately 10 times more subscriptions than in 2000 (International Telecommunications Union, 2018). Also, an estimated 3.4 billion smartphones were deployed by 2019, resulting in globally available powerful pocket computing (Belkhir & Elmeligi, 2018). Following the rapid development of ICT devices, human communication has evolved and increased in quantity and efficiency. This transformational change was enabled by the development of ICT hardware such as smartphones and computers, as well as the infrastructure (e.g., data centers and servers) and software (e.g., operating systems and applications) upon which they depend.

The material and energy inputs required to build, operate, and maintain the ICT industry are substantial (Malmodin & Lundén, 2018). As a result of this resource consumption, there is growing attention to the environmental impacts of the ICT industry. The scope of existing ICT industry level analysis includes computing devices (e.g., smartphone, tablets, desktops, notebooks, displays), communication networks, and data centers. Together, these devices and services are used to transmit, store, create, share, or exchange information.

Early studies focused on the energy impact during use of ICT devices with a limited scope, not considering the infrastructure enabling transmission of information (Van Heddeghem et al., 2014). More recently, researchers have considered the environmental impact of the entire life cycle of ICT products at a global scale, including the manufacturing, use, transportation, and end-of-life of various segments of the ICT industry. Recent studies show that the life cycle carbon footprint of the ICT industry, including the raw material extraction, manufacturing, transportation, and end-of-life, is non-trivial—an estimated net value of 710–1000 $MMTCO_2e$ by 2018, equivalent to approximately 1%–3% of global carbon emissions (Belkhir & Elmeligi, 2018; Malmodin & Lundén, 2018). The scope of that analysis include major ICT segments including smartphones, displays, notebooks, desktops, communication networks, and data centers. Estimated carbon emissions from data centers in 2020 are about 45% of the total ICT sector emissions and the highest proportion out of the emissions of all product segments (see Supporting Information Figure S1). Despite substantial energy efficiency improvement in data centers, there are concerns about the increase of the ICT industry's energy and carbon footprint primarily driven by the growth of smartphone sales and increasing data consumption from the users (Belkhir & Elmeligi, 2018; Hittinger & Jaramillo, 2019; Masanet et al., 2020).

In order to advance understanding of ICT industry's environmental impact as well as explore decarbonization pathways, it is crucial to harmonize analysis scopes and enable meaningful comparisons with the appropriate methodology. In this regard, analysis scopes and methodology for ICT companies' organizational-level carbon footprint analysis is well outlined by the GHG Protocol (WRI & WBCSD, 2004). In contrast, ICT devices' product-level environmental analyses are generally embedded with lots assumptions and have vaguely defined functional units.

In ICT product LCAs, product functionality is typically considered within the context of functional units. A functional unit refers to "measure of the performance of the functional outputs of the product system" (ISO, 2006). In practice, this measure is often defined by the LCA practitioner based on the specific product. There are many possible functional units due to the multifunctionality nature of ICT products. Variations in interpretation of product functionalities could result in inconsistencies when evaluating deeply multifunctional ICT products such as smartphones. Additionally, unclear definition of functional unit could result in difficulties in comparison. In theory, all comparative ICT LCAs should be based on function. However, in practice, the functional unit is not defined by the portfolio of functionalities that an ICT product could exhibit. A good example is that in a typical cell phone LCA, the functional unit is considered as a single cell phone device, despite the fact that a cell phone serves multiple functions, including audio, video, gaming, and computation (Suckling & Lee, 2015). Most existing smartphone LCAs published by companies show the relative contribution of product's different life cycle phases without much resolution into the impact of product functionalities, nor about variation in impacts depending on how users use different functions (Supporting Information Figure S2). According to ISO standards, a functional unit should describe quantifiable function of a product. A single smartphone device is not a quantifiable function of a smartphone, and therefore, strictly speaking, it cannot be referred to as a function unit. Rather, one smartphone unit is a reference flow. In the context of a smartphone, a possible functional unit is more accurately described as "the ability to place and receive 1095 calls over 3 years of product life-time (1 call per day on average)."

Prior research on ICT product related LCAs suggests a key role of clarifying the definition of functionality as well as approaches to model functionality-user interaction in ICT device LCA (Clément et al., 2020; Kjaer et al., 2018; Pohl et al., 2019; Suckling & Lee, 2015; Subramanian & Yung, 2017; Walzberg et al., 2019). Systematic review of 76 ICT LCA studies and reports from Clément et al. shows that product use phase, specifically the network consumption related carbon impact, is prevalent across all ICT products (Clément et al., 2020). As use phase impact is determined by specific functionality of the ICT devices as well as how they are used by the users, the impact caused from the associated infrastructure (e.g., data center, transmission stations, and wirelines) could result in variations of LCA results (Suckling & Lee, 2015). Currently, the modeling resolution as well as standardization of ICT product LCA's use phase is very limited to using average estimated energy consumption data at the device level. The lack of standardization to account for ICT products' life cycle environmental impact more comprehensively based on specific use case is a missed opportunity to drive device-level design changes to reduce products' environmental impact given the rising impact of infrastructure and network devices (Hittinger & Jaramillo, 2019). While high-level behavior effects are included in several prior ICT LCA studies, device-specific user-related effects are less often considered in the assessment. After systematically reviewing academic literature published since 2005 on LCA's contribution to the environmental assessment of ICT, Pohl et al. suggest that user-related effects of technological change is a significant gap in ICT LCA studies (Pohl et al., 2019). Furthermore, the most widely used interpretation of the functional unit in ICT device LCA as a device or object does not provide much insight into the correspondence between functionality and environmental footprint. For the user of a smartphone, knowing the environmental footprint of an average smartphone as a functional unit does not relate readily to daily device usage. The inability to make precise linkage of the production-consumption relationship through environmental impact assessment is a missed opportunity to provide information that could enable sustainable design, customer engagement, or policy decisions.

Researchers have explored approaches to better incorporate user behavior and multifunctionality as part of ICT LCA studies. Pohl et al. suggested using survey as a method to understand user behavior (Pohl et al., 2019). Judl et al. offered an initial analysis of the challenges in LCA comparisons of functional devices and identified the life cycle carbon impact of electronic devices being very different given different system boundaries (Judl et al., 2012). It also emphasizes that user behavior needs to be better understood for future studies. However, the study does not provide a systematic framework that resolves the challenges of dealing with multifunctionality in product LCA. Ryen et al. have explored approaches to incorporate consumer-relevant information to electronics LCA and demonstrated potential carbon reduction through shifting consumer electronics toward fewer but highly multifunctional devices. They build a consumer-weighted LCA approach to quantify the environmental impacts of consumer electronics product community under hybrid LCA framework. The study illustrates the net impact of the consumer electronics community increased from 1992 to 2007 primarily driven by increasing ownership and usage, despite the efficiency improvements in individual devices. The study establishes the importance of incorporating consumer behavior data and provides a more nuanced views on product functionality (Ryen et al., 2015). While the authors emphasize the importance of having highly multifunctional products as part of the intervention strategies to reduce product environmental impact from a portfolio approach, there is yet a product-level, coherent method to calculate the environmental impact of multifunctional ICT devices.

We also draw insights from product design literature on incorporating functionality as part of the product LCA process. While functionality is a key concept in product design and LCA literature, the focuses from these two communities on functionality differ. In product design, the definition of functionality is specific and tied to the way the product would be used. Product designers have considered a functionality-based architecture, where a family of products is designed systematically with embedded functional characteristics (Dahmus et al., 2001). The field of design for environment (DFE) has used functional representation to encourage design solutions toward a more sustainable society. Designers are encouraged to build "functional profiles" of products in categories such as physical lifetime, use time, reliability, safety, or human/machine interaction to better conceptualize the products' life cycle environmental impacts (Wadin et al., 2003). In addition, the framework of quality function deployment (QFD) is used to "provide a means of translating customer requirements into the appropriate technical requirements for each state of product development and production" (Chan & Wu, 2002). This framework inspired the green quality function deployment-II (GQFD-II) and environmentally conscious quality function deployment (ECQFD) methods that integrate factors such as life cycle monetary and environmental costing with quality function deployment during the product development process (Vinodh & Rathod, 2010; Zhang et al., 1999). These studies affirm the key role that functionality plays in product design, quality assurance, and environmental impact assessment. Linking these differences and harmonizing the terminology could improve the usefulness of ICT device LCAs to be relevant to a greater community.

Given the gaps and leanings from incorporating functionality as part of the ICT device LCA, we outline a method or basic "roadmap" for functionality-based LCA for ICT products that incorporates infrastructure impact and user behavior as part of the product LCA. First, we develop a mathematical method based on LCA fundamentals. Then, we illustrate the method through two case studies, starting with a less-complex case and then turning to an example of an ICT product. In the following section, we outline the definition and calculation of a functionality-based LCA framework using matrix-algebra. The matrix notation provides a succinct, generalizable, and computable description of the framework. We argue that a functionality-based LCA links users' specific interaction with products to their sustainability impacts and provides greater insights when compared to traditional product LCA. Followed by the theoretical discussion, we introduce our data collection approach and recommendations for practitioners. Finally, we present the results from the case study.

We argue in this paper that current LCA methods are limited in analyzing the nuanced impacts and trade-offs of deeply multifunctional ICT devices. A current understanding of functionality from merging the product design literature and the LCA literature could advance our understanding of this topic. In particular, incorporating a generalized, functionality-oriented perspective for ICT product LCA could help identify opportunities for impact mitigation at the individual device level. Given ICT products' global ubiquity and substantial impact, establishing responsible production and consumption relationships within the industry is particularly important.

2 | METHOD

The purpose of the study is to develop an improved LCA method rooted in the mathematical foundations of LCA (Heijungs & Suh, 2002). First, we outline the mathematical foundations of a functionality-based LCA based on the matrix-based LCA approach. In this process, we define the key terms and major steps of the assessment. Then, we introduce two critical aspects of the methods: user behavior survey and allocation approach. Finally, we perform two distinct case studies—(1) a Swiss Army knife, and (2) a smartphone—to illustrate the feasibility of the method based on their level of product complexity.

2.1 | Mathematical foundation

Life cycle assessment (LCA) is the most commonly used tool to assess ICT products' life cycle environmental impact. An ICT product LCA analysis typically includes raw material extraction, manufacturing, assembly, transportation, use, and end-of-life (Suckling & Lee, 2017). In this study, we adopt and build upon the matrix-based LCA approach codified by Heijungs and Suh. This approach was used for bottom-up, process-based LCAs and can model complex, interacting production processes and pathways using linear equations (Heijungs & Suh, 2002; Suh & Huppes, 2005). We expand on this LCA approach to model products via functionality matrices whose columns consist of functionality-specific vectors. For consistency, we maintain the general matrix form and vector notation as much as possible.

Mathematically, a product can be represented by a matrix

$$\mathbf{F} = \begin{pmatrix} | & | & \cdots & | \\ \mathbf{f_1} & \mathbf{f_2} & \cdots & \mathbf{f_n} \\ | & | & \cdots & | \end{pmatrix} \quad (1)$$

whose column

$$\mathbf{f_i} = \begin{pmatrix} f_{1i} \\ f_{2i} \\ \vdots \\ f_{ti} \end{pmatrix} \quad (2)$$

represents a functionality i. For example, in the case of a smart phone, a functionality could be calling, text messaging, email access, and internet surfing. Each entry f_{ji} denotes a material or energy input j to a specified functionality i. For consistency and simplicity, here we only consider materials and energy included in existing standard life cycle inventories (e.g., Ecoinvent) as row-wise contributors to a potential functionality. This avoids the need to expand the underlying LCA database as part of the functionality analysis and would allow ready incorporation of these methods into existing databases. As a result, **F** is a functionality matrix capturing the minimal energy and material required to facilitate a multifunctionality product.

In order to assess the environmental impact of such a product, the goal is to compute the product functionality-environmental output matrix

$$\mathbf{G} = \begin{pmatrix} | & | & \cdots & | \\ \mathbf{g_1} & \mathbf{g_2} & \cdots & \mathbf{g_n} \\ | & | & \cdots & | \end{pmatrix}, \quad (3)$$

where each column $\mathbf{g_i}$ represents the environmental outputs of functionality i. Thus, in application, instead of having one number that measures the environmental impact of a generic multifunctional product, this matrix provides an accounting of impacts based on specific product use case. Each row of the matrix captures how much each functionality contributes to an environmental output, allowing comparison of these functionalities' environmental impact.

To compute **G**, we make use of the process matrix (Heijungs & Suh, 2002; Suh & Huppes, 2005)

$$\mathbf{P} = \begin{pmatrix} \mathbf{A} \\ - \\ \mathbf{B} \end{pmatrix}. \quad (4)$$

Here, **A** and **B** are, respectively, the technology matrix and environmental intervention matrix. The columns of **P**, **A**, and **B** represent processes; the rows of **A** represent the flows of commodities associated with each process while the rows of **B** represent the environmental outputs.

To apply this to our functionality-based framework, one can think of a functionality as a linear combination of different processes. For example, suppose that functionality $\mathbf{f_i}$ is a linear combination of the processes in **P** with coefficients (weights) given by a scaling vector $\mathbf{s_i}$. Then, the following equations hold:

$$\mathbf{A}\mathbf{s_i} = \mathbf{f_i}, \quad (5)$$

$$\mathbf{B}\mathbf{s_i} = \mathbf{g_i}. \quad (6)$$

As a result, we can compute the environmental output vector $\mathbf{g_i}$ of functionality i by

$$\mathbf{g_i} = \mathbf{B}\mathbf{s_i} = \mathbf{B}\mathbf{A}^{-1}\mathbf{f_i}. \quad (7)$$

On a product level, we can calculate the total of the individual functionality-based material impact by summing up the material combination:

$$g_{prod} = \sum_i g_i. \tag{8}$$

Now, matrix algebra allows us to move these operations to the matrix level. That is, we can simply compute the entire product functionality-environmental output matrix **G** via the following equation:

$$\mathbf{G} = \mathbf{B}\mathbf{A}^{-1}\mathbf{F}. \tag{9}$$

In summary, our functionality assessment largely follows the mathematical form of Heijungs and Suh, replacing unit process vectors with functionality vectors, and extending the method to functionality-based matrix computations (Heijungs & Suh, 2002).

A critical challenge with functionality-based approaches is that the data required to specify a functionality is different. While a device such as a smartphone can be straightforwardly defined as a physical object produced by a set of interacting unit processes, a functionality requires an object, supporting infrastructure, and networks. The environmental impact of a specific functionality depends on how the consumer uses the device and thus requires understanding of user behavior, and because multiple functions are embodied in the same physical device, overlap and co-usage of certain material components are expected in nearly all cases. For example, nearly all smartphone functionalities require usage of the screen. We discuss methods to address these challenges below.

2.2 | Case study

Case study is a commonly applied method to illustrate concept applications. In case selection literature, typical case selection is recommended to be applied to probing of new mechanisms (Seawright & Gerring, 2008). Given the goal of this study is to discuss a new approach of conducting LCA, it is beneficial to consider typical cases where the approach can be applied. To investigate how FLCA can be applied, we conducted two case studies using typical case selection. The clear benefit of case study approach for this study is to provide concrete, relatable applications of the proposed approach. Additional case study materials can also provide opportunities for practitioner to explore the background data, reproduce, and further the case studies.

To illustrate the approach, we deliberately select two typical case studies including the Swiss Army knife and the smartphone. Our first case study is a well-known multi-functionality product, the Swiss Army knife. Almost everyone is familiar with or has interacted with this product. It is distinctly multi-functional by design. Due to the clear distinction of functionalities, it is straightforward to identify the product disassembly and material composition. More importantly, the Swiss Army knife intentionally tries to fit many functionalities into a single device. Therefore, it presents a similar but more tractable problem in comparison to the smartphone. The connection between the Swiss Army knife and mobile device is described by computer scientist Mahadev Satyanarayanan as "We can characterize the current design philosophy for mobile devices as the 'Swiss Army knife' approach: cram as much functionality as possible into a single device" (Satyanarayanan, 2005). The smartphone is the most widely sold and high growth ICT product around the world (International Telecommunications Union, 2018). Therefore, it serves as a good example for discussing the design and use implications of ICT products.

2.3 | User survey

User survey is a widely adopted tool in design research. It has been integrated as part of the product development process by many organizations. It enables collection of user preference data at different scales and resolutions (Brown & Eisenhardt, 1995; MacDonald et al., 2009). In this study, we choose user survey as the primary approach to collect user behavior and preferences data toward how specific product functionalities are used. We consider our case studies as pilots to test out the feasibility of the FLCA method. Given this focus, we think user survey's comprehensiveness, versatility, and efficiency could ensure the implementation and transparency of FLCA. Comprehensiveness refers to user survey's coverage of topics and specificity. For example, in one of our case studies, we ask specific questions regarding the frequency of how each functionality is used. Versatility refers to user survey's ability to be tailored for specific needs. In the case study, we ask both quantifiable metrics where functionality could be measured through frequency of use as well as qualitative open questions where the respondents can describe their motivations behind product engagement. Efficiency refers to user survey's ability to collect sizeable sample within a reasonable time frame. It also provides a pathway to scale up similar types of analysis in the future (Alreck & Settle, 2004). In the data collection, we focus on metrics relevant to user engagement based on theoretical literature in user engagement with technology. Time is a critical metric in measuring user's engagement with technology devices, particularly ICT devices (O'Brien & Toms, 2008; Suckling & Lee, 2015). While we acknowledge user engagement can refer to a range of experiences, in this study, we prioritize quantifiable user engagement metrics. Nevertheless, we encourage the research community to explore other metrics in user engagement and share additional thoughts in the discussion section.

To collect user behavior data of the first case study, we conduct online surveys using an internet-based microtask platform Amazon Mechanical Turk and request the participants to complete a Google-form based web survey. Mechanical Turk was launched in 2005 as a service to "crowd-source" tasks online and has been used as a source of subjects for social science data collection since then (Paolacci et al., 2010). Since Mechanical Turk is a relatively recent tool to be applied in academic research, we review the guidelines from the research community and follow recommended best practices (Sheehan, 2018). In the first case study, participants were adults recruited through Amazon Mechanical Turk. In the surveys, we first ask about participants' basic demographic information. We then ask about participants' interaction with the products' primary functionalities based on how much time they use each of them. The survey consists of single choice, multiple choices, and open-ended questions. The detailed questions, guidelines, as well as the IRB exemption documents, are included in the supplementary information (see SI).

For the second case study of smartphone use, we use industry average survey data, as prior studies have estimated smartphone energy use at the handset and infrastructure level (Schaefer et al., 2003). In addition, market research and non-profit agencies have been tracking smartphone's user behavior as part of the market analysis. We use data from sources such as app-based tracking and surveys in order to estimate user behavior (Nielsen, 2013; Pew Research Center, 2015). We chose to use these secondary data as opposed to primary data collection because existing surveys and market research have the benefit of large sample size and representativeness.

2.4 | Allocation approaches

Allocation is a critical topic of LCA and, therefore, needs to be further discussed for FLCA. In LCA literature, multifunctionality refers to multiple uses of a unit process or that of an output. Formulations of various types of allocation approaches are thoroughly discussed in the "Multifunctionality and Allocation" section of the Computational Structure of Life Cycle Assessment book (Heijungs & Suh, 2002). In particular, it refers to the "inevitability of the multifunctionality" as "unit processes of which the functions are deliberately coupled." The "inevitability" refers to the joint nature of the functionality. Some examples of multi-functionality from this perspective include a production process that produces chlorine and caustic soda at the same time (joint production) and a plane transporting cargo and passengers at the same time (combined production). Furthermore, Heijungs and Suh present several analytical approaches to allocation relevant to multifunctionality, including substitution, partitioning, surplus, division, linear programming, using pseudoinverse, and merging economic flows.

In this section, we discuss allocation approaches in the context of consumer products, particularly ICT products that are highly functional. We focus on the two approaches that are most widely applied in industrial analysis and multifunctionality problems: substitution and partitioning. One should note that allocation choice involves subjectivity and it is important to disclose the assumption transparently in practice. A key challenge in functionality-based LCA of multifunctional devices is the lack of one-to-one correspondence between parts of the device (or supporting infrastructure) and functions provided. For example, the screen in a multifunctional smartphone is required for nearly all tasks performed by the smartphone. How then is one to understand the impact of the screen on the environmental burdens of each functionality?

Following the allocation discussion regarding multifunctionality, we outline two approaches to address this challenge and one measure of the benefits of multifunctionality. These two approaches should be familiar to LCA practitioners: partitioning (impact of sub-uses) and displacement (or substitution, co-product displacement).

2.4.1 | Partitioning

In the case of partitioning, the impact of sub-pieces of a device or workflow that intersect more than one functionality can be allocated by fractional usage. This is intuitive: If manufacturing the screen has impact x, and 50% of screen usage is associated with a function (say, instant messaging), then the messaging functionality should be allocated $0.5x$ impact.

This allocation method requires two main steps:

1. Identify the task/functionality usage breakdown by the user during product lifetime in order to determine which functions are most important.
2. Identify the minimal combination of materials and/or supporting infrastructure required for each task/functionality.

Following the mathematical notation, we denote the environmental impact of a given functionality i as $\mathbf{g_i}$ and the fraction of time or any other alternative usage allocated unit as t_i. Matrix $\mathbf{G}$ denotes the environmental impact of a full set of functionalities. Note that because each functionality is constructed through a combination of materials of the final product, and since each row of the vector $\mathbf{g_i}$ reflects a particular environmental output, we know that the row-wise maximum of G will be less than the per-row impact of the final product $\mathbf{g_{prod}}$, calculated by the full material combination.

Let **t** be a vector denoting the fraction of time or any other alternative usage unit allocated to each functionality. The purpose is to normalize the time spent on each functionality from survey results. The resulting vector from the matrix multiplication **Gt** refers to the usage-weighted average impact of all the functionalities of the product. $t_i\mathbf{g_i}$ refers to the impact of individual functionality given its fraction of usage in unit such as number of times used or minutes spent.

Based on the definition, we know that

$$\sum_i t_i = t_1 + t_2 + \cdots + t_n = 1 \tag{10}$$

$$0 \leq \mathbf{Gt} = \left(\sum_i g_{ji} t_i\right)_j \leq (\sum_i t_i)\left(\max_i g_{ji}\right)_j \leq \mathbf{g_{prod}} \tag{11}$$

One caveat is that it would be difficult to account for multitasking. For example, if a smartphone user is simultaneously navigating and calling while using cellular data, how should we allocate the cellular energy use? While we do not have a general answer to this conundrum, we offer some possible ways to think about this question in the discussion section.

2.4.2 | Displacement

The second allocation approach one could use for multifunctionality problems in product-based LCA is displacement or substitution. A similar problem to refer to is the problem of co-production, where "a unit process is producing two or more valuable outputs" (Heijungs & Suh, 2002). Essentially, in a multifunctional device, the displacement method leads to comparing the individual functionalities with specific products that these functionalities could replace. For example, in the case of a smartphone, we can consider that a smartphone has replaced multiple devices, such as phones, pagers, cameras, video recorder, voice recorder, fax machines, and flashlights. Calculating the displacement in this case would be technically difficult, though not impossible in practice. In summary, one determines a production method to alternatively produce co-products and subtracts the impacts of these alternative production methods from the overall impact of manufacturing all co-produced products in order to arrive at the impact from the primary product.

However, the displacement approach has few challenges in implementation. First, it is challenging to identify and harmonize the technologies being displaced. For example, one could argue that a smartphone camera displaces the functionality of a pocket-style camera that could produce the same quality of images while others could argue that a smartphone camera displaces the functionality of a DSLR camera that could produce the same quality of images. The choice of displacement technology would be dependent on the prior use case and therefore challenging to standardize. Second, the displacement approach might result in negative results when the multifunctionality product is replacing a prior functionality that has significant impact. While having a negative value while using the displacement allocation method is perfectly reasonable, this could lead to confusion in applications and interpretation. Lastly, displacement has problems in that it assumes a "static" baseline in the product displaced. That is, it ignores the background technical progress that would have rendered stand-alone phones obsolete even in the absence of smartphones. In this sense, displacement assumptions could be seen as excessively "backward facing" in that they measure displacement of an inferior earlier product. For these reasons, we use the partitioning approach in this case study and only briefly discuss the implications of the displacement method in the discussion.

2.5 | Functionality factor

Multifunctionality lends itself to computing a metric of the efficiency associated with using a multifunctional product. When a product has more functions, in theory it may use resources more efficiently than single-function products. One internally consistent alternative is to compare the impact of all possible functionalities as stand-alone objects versus one single device. These stand-alone objects can be understood as individual "minimal viable product" capable of conducting a specific functionality.

For simplicity of exposition, from now on, we only consider a single specific environmental output, namely carbon emission in the form of CO_2e in grams. In particular, this simplifies the environmental output vectors $\mathbf{g_i}$, $\mathbf{g_{prod}}$ into one-row vectors, and so we can simply treat them as scalars g_i, g_{prod}. Note that the matrix **G**, in this case, reduces to a one row multi-column matrix. We introduce the notion of functionality factor and allocated

TABLE 1 Victorinox Swiss Army knife resource requirements for two exemplary functionalities

Material requirement	Functionality Cutting 1000 times using the large blade	Picking 1000 times using the toothpick
Steel (g)	177	0
Plastic (g)	104	3
Brass (g)	6	0

functionality factor:

$$\text{Functionality factor } (FF) = \frac{\sum_{i=1}^{n} g_i}{g_{prod}}, \tag{12}$$

$$\text{Allocated functionality factor } (FF_{allocated}) = \frac{\sum_{i=1}^{n} g_{i\_allocated}}{g_{prod}} \tag{13}$$

Here, g_i denotes the impact of individual functionalities and $g_{i\_allocated} = t_i g_i$ denotes the usage-allocated impact of individual functionalities.

We provide one way to understand the functionality factor (*FF*). We sum the functionality-based LCA results across all functionalities and divide those by the product-based LCA total impact assessment. This functionality factor would be 1 for a single function product: the product impact is the function impact. For highly multifunctional devices, the *FF* can be large.

One drawback of the functionality factor is that the more functionalities there are, the higher the factor will be, and the scaling can be different across products. This is solved by looking at the allocated functionality factor ($FF_{allocated}$). By Equation (11), we have that the range of $FF_{allocated}$ is between 0 and 1; therefore, it offers a normalized metric for cross-product comparison.

3 | RESULTS

We perform two distinct case studies to illustrate how the functionality-based impact assessment can be implemented. We begin with a well-known multifunctionality product, the Swiss Army knife, which has no upstream infrastructure requirements during the use phase and relatively easily quantifiable manufacturing impacts. Next, we move on to a prominent example in the ICT product category, the smartphone. We use secondary data collected from the literature to outline an initial functionality-based impact assessment. We focused on the production, use, and end-of-life phase impact for the analysis (transportation from the final assembly to customer is excluded for the case studies). Again, for the case studies impacts are communicated using CO_2 equivalent for simplicity (WRI & WBCSD, 2004). We use the partitioning allocation approach for the analysis for ease of implementation.

3.1 | Case study 1: The Swiss Army knife

The first step of the analysis is to identify the functionality as well as the corresponding resource requirements to fulfill the functionality. We outline 15 functionalities of the Swiss Army knife based on product part descriptions provided by retailer REI (Supporting Information Figure S3). Using an open-source CAD drawing provided by GrabCAD, we compile a list of 32 materials that compose the Swiss Army knife. We estimate the material type of each part based on product information. Because of the illustrative nature of this case study, we used generic material categories instead of specific engineering material names. The main materials include stainless steel (e.g., blades, corkscrew, scissors), brass (e.g., rivet washer), and plastic (e.g., caps).

For illustration purpose, the material composition of 2 out of the 15 functionalities of the Swiss Army knife are shown in Table 1 and calculated first. We assume a conservative average 60% yield factor for the materials consumption based on the upper limit of industry reported stainless steel, injection molded plastic, and copper material scrap rate (Nguyen, 2004; Reck et al., 2010). Each functionality can be calculated using the minimal combination of resources required to perform it, along with a usage metric in number of times used. In this case study, we assume each functionality to be the maximum lifetime usage number of such functionality. For instance, the material requirements for the functionality "Cutting 1000 times using large blade" can be calculated below using part mass information provided in the SI, assuming this Swiss Army knife's large blade could be used for cutting 1000 times before it breaks and gets disposed of. The disassembly of the Swiss Army knife is illustrated in Supporting Information Figure S4. We assume the complete disposal of the product after two functionalities are utilized in the first calculation for simplicity. Of course in reality, a user may continue to utilize a multifunctional product even after some of the functions are broken or un-usable.

We can write the technology matrix for these two selected functionalities of the Swiss Army knife following the well-outlined methods for life cycle inventory of a product by Suh and Huppes (Suh & Huppes, 2005):

$$\mathbf{A_2} = \begin{array}{c} \begin{matrix} \text{Steel production} & \text{Plastic production} & \text{Brass production} & \text{Electricity (assembly)} & \text{Cutting usage} & \text{Tooth picking usage} & \text{Disposal} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 0 & 0 & -177 & 0 & 0 \\ 0 & 1 & 0 & 0 & -104 & -3 & 0 \\ 0 & 0 & 1 & 0 & -6 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 \end{pmatrix} \end{array} \begin{array}{l} \text{Steel (g)} \\ \text{Plastic (g)} \\ \text{Brass (g)} \\ \text{Electricity (kWh)} \\ \text{Cutting times} \\ \text{Picking times} \\ \text{Disposal} \end{array}$$

The column indicates steel production, plastic production, brass production, electricity production (for electricity used during product assembly), use of the Swiss Army knife for cutting, use of the Swiss Army knife for tooth picking, and disposal of the knife. Each row is assigned to steel (g), plastic (g), brass (g), electricity (kWh), number of times the cutting function is used, number of times the tooth picking function is used, and disposed Swiss Army knife (unit).

The environmental intervention matrix and the functionality matrix are given by

$$\mathbf{B_2} = \begin{pmatrix} 4.8 & 7.8 & 9.2 & 0.4 & 0 & 0 & 0.1 \end{pmatrix} \tag{14}$$

where each row entry represents the environmental intervention for a specific material of production process. For the case study, we use carbon emission as the main evaluation metric due to its high inventory data reliability. We also use industry-based life cycle inventory for the calculation and acknowledge that these data only provide a first-order approximation of potential impact and that they are generally not process or product specific. Specifically, we use inventory and emissions data acquired from a comprehensive life cycle inventory database EcoInvent 3.5 (Wernet et al., 2016). Therefore, the unit for the environmental intervention matrix $\mathbf{B_2}$ is g CO_2e:

$$\mathbf{F_2} = \begin{pmatrix} | & | \\ \mathbf{f_1} & \mathbf{f_2} \\ | & | \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1000 & 0 \\ 0 & 1000 \\ 0 & 0 \end{pmatrix}, \tag{15}$$

where $\mathbf{f_1}$ represents cutting 1000 times using the large blade and $\mathbf{f_2}$ represents picking 1000 times using the toothpick.

We can calculate the carbon footprint of the functionality of two representative functionalities of the Swiss Army knife outlined in the case study section based on partitioning allocation approach. We follow the algorithm provided above in Section 2.1. We illustrate the calculation of the two example functionalities as

$$\mathbf{G_2} = \mathbf{B_2}\mathbf{A_2}^{-1}\mathbf{F_2} \tag{16}$$

$$= \begin{pmatrix} 1716.4 & 23.4 \end{pmatrix} \tag{17}$$

This means our estimated carbon footprint of the Swiss Army knife performing cutting functionality 1000 times using its large blade is 1716.4 g CO_2e and it performing tooth picking functionality 1000 times using its toothpick is 23.4 g CO_2e.

In addition, we collected user data ($n = 100$) through online web-survey to understand users' interaction with the Swiss Army knife. The results of the functionality-based impact assessment are presented below with incorporation to user frequency of different functionalities of the Swiss Army knife (Table 2). The details of the survey and usage allocation calculation are provided in Part II of the Supporting Information.

TABLE 2 Summary of selected functionalities' user survey results (n=100) and corresponding carbon footprint

	Cutting using the large blade	Picking using the toothpick
Number of respondents using this functionality approximately once a day	14	10
Number of respondents using this functionality approximately once a week	39	20
Number of respondents using this functionality approximately once a month	29	24
Number of respondents using this functionality approximately once a year	11	20
Number of respondents who never use this functionality	7	26
Average times used assuming 1000 times total product lifetime use	110	43
Average usage allocation (%)	11.05	4.31
Total carbon footprint (g CO_2e)	188.8	1.0

Therefore, if we account for the estimated use times from the survey, we could redefine the functionality matrix as below and calculate the corresponding impacts:

$$\mathbf{F_2} = \begin{pmatrix} | & | \\ \mathbf{f_1} & \mathbf{f_2} \\ | & | \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 110 & 0 \\ 0 & 43 \\ 0 & 0 \end{pmatrix}, \tag{18}$$

$$\mathbf{G_2} = \mathbf{B_2}\mathbf{A_2}^{-1}\mathbf{F_2} \tag{19}$$

$$= \begin{pmatrix} 188.8 & 1.0 \end{pmatrix} \tag{20}$$

Now we expand the analysis to account for all of the 15 functions of the Swiss Army knife (see Supporting Information Figure S3). We can solve the impact using calculation from a 20 × 20 technology matrix. Results show that it is a highly multifunctional device with varying range of impacts of the functionalities:

$$\mathbf{G}_{15} = \mathbf{B}_{15}\mathbf{A}_{15}^{-1}\mathbf{F}_{15} = \begin{pmatrix} \overset{\text{Tweezer}}{0.4} & \overset{\text{Large blade}}{188.8} & \overset{\text{Can opener}}{105.3} & \overset{\text{Reamer, punch}}{53.5} & \overset{\text{Corkscrew}}{115.6} & \cdots & \overset{\text{Scissors}}{18.9} \end{pmatrix} \tag{21}$$

Based on the functionality factor (FF) we introduced, in the case of the Swiss Army knife we can calculate the functionality factor as the ratio of the sum of all functionalities versus the total device production carbon footprint:

$$FF_{\text{Swiss Army knife}} \approx \frac{10.0 + 1709.1 + 1666.3 + 1647.2 + 1661.5 + \cdots + 23.9}{2103.7} \approx 9.6 \tag{22}$$

This implies that the Swiss Army knife, by combining multiple functions into one, avoids the impacts of 15 separate devices with an impact ≈10 times as large.

On the other hand, $FF_{allocated}$ can give a different view. According to the survey results, the total allocated functionality factor for all 15 functionalities is

$$FF_{\text{allocated}} = \frac{\sum_{i=1}^{n} g_{i\_allocated}}{g_{prod}} \tag{23}$$

$$\approx \frac{0.4 \times t_1 + 188.8 \times t_2 + 105.3 \times t_3 + 53.5 \times t_4 + 115.6 \times t_5 + \cdots + 18.9 \times t_15}{2103.7} \tag{24}$$

$$\approx 0.61 \tag{25}$$

where the time spent on each functionality is calculated via the user survey and normalized. While FF indicates the highly efficient nature of the Swiss Army knife. The $FF_{allocated}$ can indicate the degree to which the functionality is utilized. $FF_{allocated}$ can give a sense if the multifunctional device is being underutilized in a sense. Consider, for example, a user who only uses the toothpick functionality of the Swiss Army knife. That is, the usage fraction = 100% for the "picking using toothpick" function and 0% for all others. The resulting $FF_{allocated}$ would be quite small. This implies that the "efficiency" of use of the device is low, in that the user purchased a carbon-intensive multifunctional device only to provide a single simple function. That user would have produced much less impact by only purchasing a simple reusable toothpick.

In a sense, our approach could be considered complimentary to displacement. Displacement asks: What did we replace by having multiple functionalities in one product? It does not ask about the efficiency of such replacement based on the usage. If a product carries 20 functionalities but the user only uses 2, then there could be lower emission impact if the user bought 2 separate smaller products instead of a product that carries all these extra unused tools. As a result, without factoring into allocated usage, individual impact could be high. However, factoring into the distribution of usage, we could understand the efficiency of the multifunctional product through the allocated functionality factor, which is always between 0 and 1 (the numerator is never larger than the product footprint). In the case of the Swiss Army Knife, every functionality impact will include that of the enclosure because it is part of the minimum requirement for usage of such functionality. If the user does not use multiple functionalities, such enclosure could be made much smaller and thus reduce the impact. However, if a minimal enclosure is shared between all functionalities that are used frequently, then we reduce the impact of the larger sum of multiple smaller enclosures.

3.2 | Case study 2: Smartphone

Our next case study is a smartphone. Similar to the Swiss Army knife example, the first step of the analysis is to identify functionalities that one device fulfills. After that, we can map these functionalities with corresponding resource requirements. ICT products, particularly smartphones, are used to facilitate a range of activities from calling to watching entertainment. Smartphones have a range of possible functionalities, including phone calls, text messages (SMS), video, audio, web browsing, and email. Each functionality is supported by a set of hardware, software, as well as energy inputs and connections to broader information infrastructure. The multifunctionality nature of smartphone has been explored in academic studies (Nielsen, 2013; Paiano et al., 2013; Schaefer et al., 2003; Suckling & Lee, 2015). To streamline the analysis, we leverage a framework proposed to evaluate the energy impact of Internet of Things devices and incorporate LCA approach (Hittinger & Jaramillo, 2019). We consider the direct energy draw from the device as well as the indirect energy and resource consumption. Under this framework, a functionality-based evaluation of a smartphone's environmental impact can be described as

$$\mathbf{G}_{\text{functionality}} = \mathbf{G}_{\text{device}} + \mathbf{G}_{\text{infrastructure}} + \mathbf{G}_{\text{supply chain}} + \mathbf{G}_{\text{behavioral}}, \tag{26}$$

where the four components are noted with increasing order of complexity in the equation.

- $\mathbf{G}_{\text{device}}$ = Environmental impact of direct (local) energy of device components;
- $\mathbf{G}_{\text{infrastructure}}$ = Environmental impact of remote energy use for the supporting infrastructure. In the following analysis, we use $\mathbf{G}_{\text{infrastructure}} = \mathbf{G}_{\text{network}} + \mathbf{G}_{\text{data center}}$;
- $\mathbf{G}_{\text{supply chain}}$ = Environmental impact of energy and resource use associated with device production;
- $\mathbf{G}_{\text{behavioral}}$ = Environmental impact of indirect energy and resource of device through behavioral changes of the user.

For the following case study, we consider the first three levels of impact in the equation. The behavior level impact is considered out of scope for this case study. To analyze the functionality-based environmental impact of a smartphone, we construct a representative smartphone with credible and detailed case studies from the literature. The following case study uses a combination of secondary data based on availability and fit because publicly available smartphone LCAs have limited data granularity at the component level. We select the top three most popular activities for the case study, namely text messaging, voice/video calls, and internet surfing along with an additional emerging activity that has gained popularity in smartphone devices: virtual reality (VR) activity (Pew Research Center, 2015) (Figure 1).

To calculate device and infrastructure level impact, we obtain energy consumption estimations at device, at network, and at data centers using mobile phone end-to-end energy consumption power model. The energy consumption power models use actual measurements of equipment energy consumption and data traffic flow to estimate the energy consumption under various use scenarios. We primarily use the modeling results from Yan et al. and supplement with network energy consumption estimation from Malmodin to be more accurate. Specifically, we use the basic connectivity service power consumption of 2 W per mobile 4G subscriber and add additional energy requirements based on 1 W/Mbps rate and data traffic under different use scenario (Malmodin, 2020; Yan et al., 2019).

The testing condition for the following three use cases are listed below based on the experimental setup by the latest literature (Yan et al., 2019). We calculated the energy consumption in Table 3 based on the assumption that energy consumption have a linear relationship with time (Yan et al.,

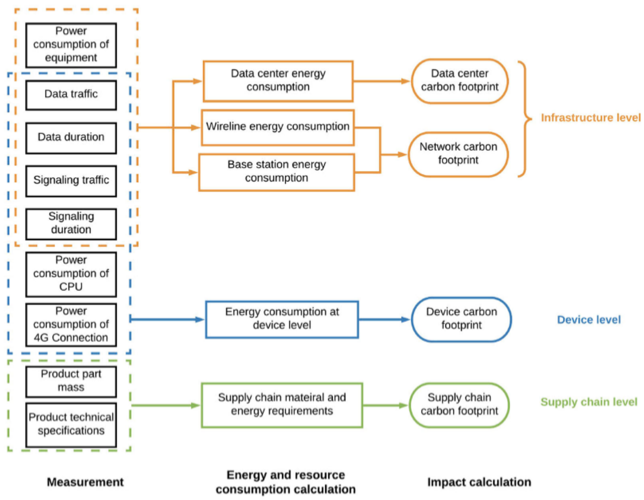

FIGURE 1 ICT product functionality-based LCA calculation approach (based on Malmodin, 2020; Yan et al., 2019)

TABLE 3 Energy consumption breakdown of exemplary smartphone functionalities (calculated based on Malmodin, 2020; Yan et al., 2019)

	Texting	Web browsing	Video chat	VR
Device-level energy consumption (W)	0.320	0.663	0.731	0.961
Network energy consumption (W)	2.001	2.711	2.790	9.603
Data center energy consumption (W)	0.001	0.042	N/A	2.414

2019). For validation, we consulted industry expert to validate the energy consumption values.

- **Texting**: type and send a 16-Chinese character text message via WeChat
- **Web browsing**: use built-in browser to open m.sohu.com
- **Video chat**: chatting via video via WeChat
- **VR**: use Orange VR to open a video (length = 65 s, size = 58 MB)

We make few major assumptions through using this set of energy consumption data. First, we define network as both mobile and fixed network data services therefore include power consumption calculation of both infrastructure. Second, power consumption at the smartphone device level is estimated using the power consumption measurements of CPU and 4G network connection. Third, the device-level energy consumption was measured for particular smartphone devices (Samsung Galaxy 7 and Huawei Honor 5X) and tested under different use scenarios.

Note that the majority of the impact happens at the network infrastructure level. To estimate the relevant carbon impact of example functionalities, we use publicly available data on smartphone user behavior and the average US grid emissions factor provided by the US EPA to compute the carbon footprint. We estimated the average user interaction with the functionality using US average data in 2017 in Supporting Information Table S4 as proxies (Text Request, 2017). Minutes of use estimations are rounded. We use 3 years as the average product lifetime.

Carrying out this computation using the information from Table 3 and SI Table S4, we first write the technology matrix as following (see SI part II for more details of the matrix):

$$\begin{array}{c} \quad\quad\quad\quad\quad \text{Production and energy} \quad\quad\quad\quad\quad\quad \text{Texting} \quad \text{Web browsing} \quad \text{Video chat} \quad \text{VR} \quad \text{Disposal} \end{array}$$

$$\mathbf{A_4} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -0.35 & -0.73 & -0.80 & -1.05 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -2.19 & -3.01 & -3.06 & -13.16 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 65700 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 65700 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 65700 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 65700 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & -1 \end{pmatrix}.$$

Next, we formulate the environmental intervention matrix and the functionality matrix as

$$\mathbf{B_4} = (22.5 \quad 1.9 \quad 2.7 \quad 1.3 \quad 1.9 \quad 0.5 \quad 0.1 \quad 4.81 \quad 0.2 \quad 0.453 \quad 0.453 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0.1), \tag{27}$$

where each entry of $\mathbf{B_4}$ represents the pollution in the form of carbon emissions generated from the corresponding module production process or electricity generation during certain operation time. We refer to the carbon emissions of Fairphone 2 for the key module's emissions (Proske et al., 2016). For the electricity consumption at device and infrastructure level, we use 2016 eGrid output 0.453 $kgCO_2e$/kWh as the proxy emissions factor based on US average (US EPA, 2015)

$$\mathbf{F_4} = \begin{pmatrix} | & | & | & | \\ \mathbf{f_1} & \mathbf{f_2} & \mathbf{f_3} & \mathbf{f_4} \\ | & | & | & | \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 12897 & 0 & 0 & 0 \\ 0 & 23360 & 0 & 0 \\ 0 & 0 & 6083 & 0 \\ 0 & 0 & 0 & 23360 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \tag{28}$$

where $\mathbf{f_1}$ to $\mathbf{f_4}$ represent the estimated minutes each function is used during the products' lifetime based on literature and surveys. Recall that each of these columns represents the four functionalities: texting, web browsing, video chat, and VR in that order, with relative usage assumption given in Supporting Information Table S4 but normalized to a total of 65,700 min, that is, 3 h per day for 3 years, of use.

Similar to the Swiss Army knife case study, we can calculate the carbon footprint of the selected functionalities of the smartphone based on partitioning allocation approach. We follow the algorithm provided in the Methods section and calculate the functionality-based impact (in $kgCO_2e$) as

$$\mathbf{G_4} = \mathbf{B_4}\mathbf{A_4^{-1}}\mathbf{F_4} \tag{29}$$

$$= \begin{pmatrix} 6.67 & 12.27 & 3.50 & 15.09 \end{pmatrix} \tag{30}$$

To get a sense of the maximum range of the impacts, let us assume a user uses each functionality for 6 h every day for 3 years. We then modify the entries of each column in $\mathbf{F_4}$ as 394,200, referred here as $\mathbf{F_{4max}}$. We can compute the impacts as

$$\mathbf{G_{4max}} = \mathbf{B_4}\mathbf{A_4^{-1}}\mathbf{F_{4max}} \tag{31}$$

$$= \begin{pmatrix} 203.76 & 207.03 & 226.55 & 254.68 \end{pmatrix} \tag{32}$$

Note that in these cases, the range of impacts for different functionalities is quite large. This makes intuitive sense because the difference in energy consumption in the selected use cases vary significantly (as shown in Table 3) . We should also note that the values from this case study rely on testing or evaluation results of specific units or brands. The main point of the case study is to illustrate an evaluation process. Assessments of different types of ICT products by different manufacturers could be conducted on a case by case basis.

To calculate the functionality factor, we need to compute the product life cycle carbon emissions of 39.36 kgCO2e, which comprises (1) 35.98 kgCO2e manufacturing phase emission (Proske et al., 2016), (2) 3.28 kgCO2e use-phase emission, under the assumption of energy consumption and power grid emission as above, and (3) 0.1 kgCO2e of assumed end-of-life emission. The functionality factor is thus

$$FF_{\text{smartphone}} \approx \frac{6.67 + 12.27 + 3.50 + 15.09}{39.36} \approx 0.95 \tag{33}$$

Using the relative time consumption of these four functionalities as reported in SI Table S4, we have $(t_1 \quad t_2 \quad t_3 \quad t_4) \approx (0.20 \quad 0.36 \quad 0.09 \quad 0.36)$. Therefore, the allocated functionality factor for these four functionalities is:

$$FF_{\text{smartphone, allocated}} \approx \frac{0.20 \times 6.67 + 0.36 \times 12.27 + 0.09 \times 3.50 + 0.36 \times 15.09}{39.36} \approx 0.29 \tag{34}$$

Next, we consider a hypothetical comparative case to illustrate how functionality-LCA can enable more direct comparison of ICT device LCAs. In the Fairphone 2 LCA, the CPU has a die size of 111.28 mm^2, which was identified through x-rays and grinding of the chip. Consider an upgraded version of this smartphone with more powerful processor, of which the die size is 1.1 times larger at 122.41 mm^2. Based on Tables 3–8 of the Fairphone 2 LCA study, the estimated increase due to processor upgrade is approximately 0.6 kgCO2e (Proske et al., 2016). We can update the environmental intervention matrix accordingly as

$$\mathbf{B_{4U}} = (23.1 \quad 1.9 \quad 2.7 \quad 1.3 \quad 1.9 \quad 0.5 \quad 0.1 \quad 4.81 \quad 0.2 \quad 0.453 \quad 0.453 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0.1) \tag{35}$$

As a result of the processor upgrade, we assume the device-level energy increases by 5%; therefore, we modify matrix $\mathbf{A_4}$ by multiplying the 12th to 15th columns of the 10th row with 1.05. If we assume user behavior is unchanged, we can calculate the new impact as $\mathbf{G_{4U}} = (6.78 \quad 12.48 \quad 3.55 \quad 15.31)$. In this case, the allocated functionality factor changes very little and remains 0.29 after rounding. However, if we assume that the upgraded processor results in a relative increase in user's engagement in the VR functionality by 20 min, the allocated functionality factor improves to 0.30 since the user increases their usage of the function that requires the largest amount of carbon to produce. This signifies that the upgrade suits the needs of users at the cost of higher carbon impact. However, on the flip side of the coin, for users who spend more time texting, for example, spending twice as much time texting and the same amount of time for the other three functionalities, the allocated functionality factor is only 0.26, which shows that the upgrade is wasteful.

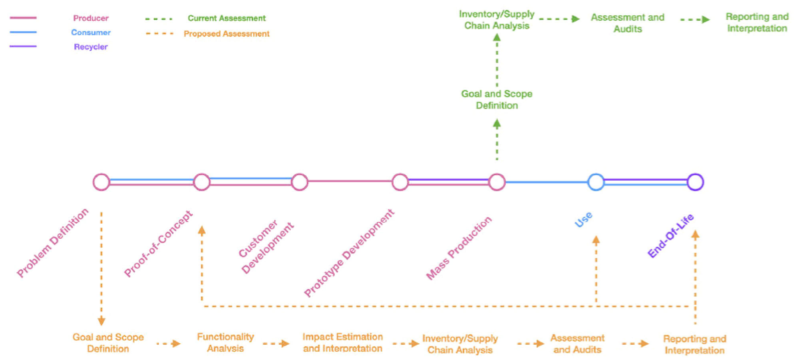

FIGURE 2 Comparison of current versus proposed assessment framework based on product life cycle milestones (blue outlines life cycle steps relevant to consumers)

4 | DISCUSSION

4.1 | Role of functionality in ICT life cycle assessment

The functionality-based perspective offered in this paper merges functionality-based thinking in product design with existing LCA frameworks. Specifically, functionality-based life cycle assessment (FLCA) could serve as an early assessment tool for designers to better incorporate user preferences or behavior as part of the product development cycle and supply chain planning. For every product in the ideation stage, a user preference matrix could be constructed and mapped with its corresponding functionality. Early assessments by functional modules could enable designers and manufacturers to identify emission reduction opportunities in the early stages of product development. It also enables additional scenario analysis and assessments of alternative design and manufacturing choices (Figure 2). As illustrated, the functionality analysis step will allow producers and designers to clearly articulate the functionality they would like to address as part of the product development process. This step provides a key piece of data needed to complete a FLCA. However, to enable FLCA to become more mainstream, there needs to be training and dialogues required to familiarize product teams with this concept. In particular, cross-functional dialogues that involve designers and engineers who are familiar with LCA could catalyze and potentially improve FLCA analysis.

As illustrated by the case study, high-quality publicly available data on how product design maps to specific functionalities are rare in the ICT product space. In the Swiss Army analysis, when data are complete and tractable, the analysis is higher quality and more informative. Therefore, we encourage ICT product designers and producers to actively collaborate with the research community to build more comprehensive baseline data for the functionality analysis.

It is worth noting that the total emissions calculated is decomposable because it consisted of a fixed piece to which we add a different calculation of emissions from use. In practice, the analysis could be separated into fixed versus variable to allow replication of calculations for multiple profiles or use cases.

We offer some strategies to FLCA implementation as part of the product development cycle in the SI. FLCA is iterative in nature because design changes could happen during the product development cycle. It is important to update the data to reflect such updates. FLCA can accommodate a wide range of computational tools. As illustrated in the case studies, depending on the complexity of the analysis, a user can build simple computational models in commonly used software such as excel, MATLAB, or Python. In addition, it could be incorporated as part of the LCA software, where the software allows the user to define their own functional module during the product design process. Then, the software could perform analysis based on the pre-defined functional module and output environmental impacts of these functional modules accordingly.

We introduce the functionality factor (FF) to compare the impact of all possible functionalities as stand-alone objects versus one single device. FF provides an internally consistent approach to consider the role of multifunctionality in product design. An alternative approach is to consider product displacement, where the environmental footprint of each product functionality can be displaced with a product with only one or limited functionality. However, we caution that the selection of displacement product could be biased. In the case of the Swiss Army knife, we can calculate the functionality factor as approximately 10. The functionality factor conceptualizes the environmental "savings" as a result of shared structural support for multiple functionalities.

We expect the FF for smartphone is similarly high because of the shared computational and structural support for many functionalities. One interesting observation about communication products is that in early days, products were designed in a more modular fashion. A notable example is the Siemens S55 introduced in 2002, where the phone has a separate camera and cell phone module that could function independently (Schischke et al., 2019). As phones become more integrated, their FF is likely to increase. However, while the integrated design created environmental "savings" from the functionality perspective, the actual environmental impact is dependent on how user interacts with the products. It is possible for a product to have a high FF value but a small allocated FF value, indicating that there is a mismatch of the intended functionality designed by the manufacturer and the utilized functionality by the user. As device manufacturers are considering for improvements for repairability, recyclability, and upgradability, it is important to consider how to optimize these two factors from a design perspective. It could be that simpler products tailored to individual use cases may have less impact overall.

Lastly, a functionality-based perspective enables ICT product designers and consumers to include the sustainability impacts of hardware versus software into their consideration. For example, certain functionality such as storage can be achieved through on-device storage integrated circuits such as flash memory or via software and application services in the cloud. Evaluation of these different functionality options could help optimize the environmental footprint of ICT products.

4.2 | Limitations

Due to the costly and proprietary nature of electronics life cycle data, our case studies are limited in data quality, consistency, and completeness. However, since the purpose of this piece is to illustrate a novel approach, we focus on the problem formulation and process of conducting such assessment. It is our hope that this piece opens up possibilities for scholars and practitioners to adopt a functionality-based perspective in design and LCA of ICT products and beyond.

Given the rapid development in the ICT space, studies that are completed few years back could be outdated. We also acknowledge that survey methods have constraints in reliability and ability to understand people's decision-making process in-depth (Rossi et al., 2013). We use industry-average product lifetime data, which could be further specified in more detailed case studies based on rigorous product lifetime estimation approach (Zhilyaev et al., 2021). In regard to metrics used, we mainly focused on the carbon footprint. Aside from carbon footprint, ICT product waste has a substantial impact on the environment in metrics such as toxicity, water, and soil quality (Chen et al., 2018; Wu et al., 2015). In addition, even though we tried to delineate the functionalities of ICT products, we acknowledge that due to the co-dependence of parts and components of ICT products, it is challenging to completely isolate the impacts of each functionality. Simple addition or substitution of a function might not be sufficient to address the co-dependence of the parts of ICT products. Although the perspective and allocation methods offered on ICT product multifunctionality in this paper are simplistic, it helps to assess the topic of defining the functional unit(s) for multifunctionality products in consequential LCA and the consideration of system expansion (Zamagni et al., 2012). Finally, we do not address the impacts of ICT technology on human behavior here, although such impacts are critical for multi-functional LCA outcomes. While we provide scenarios on how ICT products such as smartphones could change people's behavior through its various functionalities, we think experiments with clear controls and boundaries are most suited for further exploration.

The case studies are limited due to the choice of allocation. While we stated the challenges in using the displacement allocation approach, we acknowledge that one way to understand the environmental impact of additional functionality is through comparing the individual functionalities with specific products that they could replace. For designers who have specific baseline devices in mind, the displacement allocation approach could be more informative.

In the smartphone functionality-based LCA case study, we consider the carbon impact of user behavior out of the analysis scope. We acknowledge that there is a lack of higher resolution user behavior data that map to specific user behaviors in the study. Filling this data gap could enable a more comprehensive evaluation of the sustainability impacts of ICT products.

5 | CONCLUSION

This study develops and implements an LCA framework that highlights the linkages among user behavior, product functionalities, and product environmental footprints. As illustrated by the two case studies, a functionality-based LCA provides a systematic approach to view the environmental impacts of multifunctionality products. It builds on existing foundations of LCA to more comprehensively capture the life cycle environmental impact of multifunctional products such as smartphones. Taking on a functionality-based perspective helps designers and consumers see a fuller picture of products' environmental impact at the device, infrastructure, supply chain, and behavioral level. This framework creates opportunities in corporate sustainability and public policies toward sustainable production and consumption.

From the perspective of corporate sustainability, a functionality-based approach spans silos into which emissions are sometimes counted in a way that is necessary to understand to reduce emissions effectively. Much of the space of ICT products has considered impacts after product launch. This new framework helps analyze many different unexpected impacts depending on how functionalities replace one another or don't. The design relevance of this framework could enable private sector actors to be much more powerful participants in emission reductions, as encouraged by international treaties such as the Paris Agreement. Existing assessment frameworks such as the integrated assessment models focus on the social-economic interactions at the macro-scale. The functionality-based LCA framework fills in a gap in the assessment space where micro-scale, granular design efforts could be modeled and simulated.

From the perspective of public policy, this approach creates a system view necessary for effective climate and sustainable-development policy. Existing product LCA approaches for consumer products may enable understanding of where emissions are coming from. However, they do not necessarily shed light on the interconnections between device production and consumption. Addressing these interconnections is key to informing effective policy design and to assessing unintended consequences or benefits from these policies. Specifically, a functionality-based approach effectively encompasses the many factors inherent in emissions arising from any given ICT device. This approach compliments current material-focused perspectives on product environmental footprint and extends the system boundary to consider infrastructure and user behavior. The results of the functionality-based analysis could help climate policy makers identify and forecast the potential sources and impact of greenhouse gas emissions along a broader scope of supply chains.

In addition, this study leads to some interesting open questions to be looked into in the future. Incorporating functionality as a core aspect in consumer products' LCAs opens up possibilities to deep-dive into user behavior and product design. In regards to user behavior, the most important unanswered question is how to systematically evaluate the behavior level impact of ICT devices, as they are typically considered out of scope for device-level life cycle assessments. From a climate impact mitigation perspective, it is crucial to understand how ICT devices track and impact individual's behaviors in areas such as consumption, transportation, and communication. While there is a streamlined process to collect data during product manufacturing and device-level energy consumption, there is little methodological framework to rely on in order to meaningfully capture digital behavior data as part of ICT product environmental footprint assessment. In regards to product design, this study offers possibilities to explore historical evidence of ICT product displacement. One exercise could be collecting the historical data of single-functionality products' environmental footprint and product lifetime and compare with multifunctionality products. One could imagine that while ICT product might have more functionality over time, their service life time might decrease or fluctuate based on the technological complexity (Zhilyaev et al., 2021).

Using a functionality-based lens to investigate question related to product durability could provide empirical evidence of how different ICT product designs have impacted the environment and what the trend looks like over time. Such questions fall within the consequential life cycle assessment literature, where impacts of processes are evaluated based on the consequences of production and use (Zamagni et al., 2012). In digital technology related LCAs, consequences of different technology-enabled functionalities have not been a focus of study. For instance, one could further explore the environmental impacts of the services of digital products beyond the physical materials (Wolfson et al., 2019). We hope a functionality-based approach encourages more thinking toward the potential environmental burdens of the technology choices.

ACKNOWLEDGMENTS

We thank Nhi Truong, Laura Bogar, Ben Moran, Dan Iancu, Ines Azevedo, and Chris Field for reviewing the study draft. We thank Jens Malmodin and Jonathan Koomey for offering their expertise in data center and network energy consumption. We thank the Amazon Mechanical Turk Workers who participated in this research both during pilots and implementation. This research was performed under Stanford University Institutional Review Board (IRB) Protocol IRB-46371. Stanford's IRB can be reached at humansubjects@stanford.edu

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Github at https://github.com/linshigreenfire/FIA

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SUPPORTING INFORMATION

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How to cite this article: Shi L, Mach KJ, Suh S, Brandt A. Functionality-based life cycle assessment framework: An information and communication technologies (ICT) product case study. *J Ind Ecol*. 2022;1–19. https://doi.org/10.1111/jiec.13240