The Footprint of Things: A hybrid approach towards the collection, storage and distribution of life cycle inventory data

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Abstract

Life cycle assessment is a well-established methodology for assessing the environmental impacts of products and services. Unfortunately, an essential part of this life cycle assessment method, collecting inventory data, is extremely time consuming. The quality of manually conducted LCA studies is often limited by uncertainty in the inventory data or narrow scope. Past attempts to overcome these challenges through automation of data collection utilizing the Internet of Things have relied on fully centralized architectures. The drawback of a central repository is the complex coordination between all involved actors in supply chains of products and services. This paper proposes an alternative hybrid approach combining a primary distributed system supplemented with a central repository reducing the need for coordination. This hybrid approach is named "the Footprint of Things". We present a system design that embeds the automatic reporting of life cycle inventory data, such as energy and material flows, into all product components involved in a service delivery. The major strength of our novel system design, among others, is its capacity for real-time and more precise impact calculation of ICT services.

1 Introduction

Life Cycle Assessment (LCA) is a standardized methodology to measure and evaluate environmental impacts associated to all stages of a product life cycle [15]. The application of LCA in product design, production processes or supply chain monitoring supports their sustainability [1]. However, the collection of timely and accurate inventory data, an essential component of the methodology, is still a major challenge for practitioners [14, p 194].

There are several causes that make efficient data collection difficult. Among these are the high cost in terms of time and resources associated to the collection of inventory data, the structural complexity of supply chains, the lack of transparency in the supply chain, and the ongoing changes in manufacturing processes [17, 36, 14]. However, recent developments in communication technology, such as Radio-frequency Identification (RFID), have brought about new ways to improve data inventory management [22]. Also, the potential utilization of the Internet of Things (IoT) provides a number of unique opportunities to solve problems in the field of industrial ecology [21]. In this paper we study how the promising IoT concept could be integrated to automate the collection of Life Cycle Inventory (LCI) data in order to enable real-time reporting of environmental impact of products or services. Although the findings are relevant to the application of LCA in general, we are particularly concerned with the assessment of ICT and digital services.

The IoT is a powerful but broad paradigm without a concise and widely agreed to definition [5]. Initially, the term was coined in relation to the use of RFID technology in supply chains in order to observe and understand objects in the real world [4]. The more prevalent and often cited definitions of the IoT generally take a wider perspective and consider it to be "a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols" [16] or "a dynamic global network infrastructure with self configuring capabilities based on standard and interoperable communication protocols where physical and virtual 'things' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network" [30].

As presented in the related work (see Section 2), a number of researchers propose, describe, prototype and implement LCI systems based on IoT infrastructure. The majority of studies experiment with the idea of installing sensors (e.g. energy meters) on existing equipment used in the supply chain. Other promising use of sensors for accounting the LCI include weight and flow analysis in production, position and movement sensors for transportation, and (e.g. electricity and fuel) consumption sensors for measuring during the product operation. Additionally, in some studies the products themselves are equipped with (wireless) communication capabilities and connected to a central repository where data is collected and analyzed. However, to the best of the authors' knowledge, there is no existing approach that considers the product, rather than a centrally operated information repository, as a carrier for inventory data. With the product as the data carrier, the responsibility of data collection can be decomposed into smaller units. Moreover, it removes the need for central data governance. This allows more flexible integration of various LCI information flows to report on the life cycle of products and their components. Such a decentralized design can then be augmented by a central data repository – resulting in a hybrid architecture that combines the strengths of both approaches.

This paper presents the design of such a hybrid architecture named "the Footprint of Things" (FoT). The FoT enables life cycle assessment (e.g. carbon footprinting, water footprinting) on the basis of data collected via the IoT. The approach allows for a unified, multi-vendor system that can *gradually* be adopted by industry in order to distribute LCI data. The system is primarily based on a decentralized architecture to store and distribute data. We define the FoT concept as a bottom-up distribution mechanism for LCI data, collected during all phases of a product life cycle, by storing this data primarily onto the components of a product. The fundamental reason to utilize the IoT infrastructure is the ability to collect more specific inventory data on a particular instance of a product as opposed to the practice of using averages for whole product series. This simplifies the environmental impact calculation for services running on the product and provides more accurate LCI data. As part of the design of the FoT the distributed IoT network is complemented with a central repository that supports long term inventory data storage and discovery. The combination of both architectures enables flexible composition of inventory hierarchies that are both specific and efficient.

In our research we apply the design science methodology of Peffers et al. [26]. Firstly, we review the LCA methodology with a particular focus on the collection of inventory data. Secondly, we develop an architecture for a bottom-up collection of LCI data. Concepts from the IoT are used as a basis for its design. To understand this FoT architecture better, we also create an information flow model that helps explain and reason about the collection, storage and communication of information in the FoT. Finally, we examine the potential effects and challenges that may result from our proposed FoT mechanism. One of our main concerns hereby is the issue of personal privacy, as improved footprint information should not come at the expense of civic liberties.

The remainder of the paper is as follows. Section 2 presents the related work on systems utilizing the IoT to facilitate LCI data collection and distribution. Section 3 describes the challenges related to the environmental assessment of ICT and digital services and considerations in conducting life cycle analysis studies. Furthermore, it lists the implications for each of the steps of a LCA study when constructing the impact calculation using the FoT. Section 4 presents the FoT system design and explains how life cycle inventory data could be measured, collected and communicated through the different product stages. In Section 5, we reflect on our design by addressing the architectural and social challenges that would result from integration of the FoT concept into a supply chain. Finally, Section 6 concludes with an outlook on future work to address the identified challenges.

2 Related Work

Several studies have applied the IoT as a means to improve LCI data flows using a central data repository to collect and distribute the LCI information. For example, the studies [32, 31] present a central system that captures LCI data and operating data of manufacturing equipment, such as the running status and current temperatures of the machinery. These systems are capable of dynamic real-time collection of LCI data but are missing the benefits in flexibility and accuracy of a system that stores and distributes data in a decentralized way. In a similar way, the authors of [39] propose a dynamic and real-time method to collect energy consumption data based on the IoT. In their approach machines utilized within the life cycle of a product are equipped with energy sensors and communication technology. All the sensors are connected to a central cloud environment where the energy life cycle costs of a product are calculated. The automation of carbon footprinting through dynamic power sourcing in solar photovoltaic systems is proposed in [35]. While the photovoltaic sector traditionally relied upon static carbon footprint averages to calculate the footprint of solar panels during use phase, in [35] automatic IoT-based carbon footprinting approaches are evaluated. The study finds that the dynamics of the power sourcing throughout the supply chain can be sufficiently captured for improved estimates of carbon footprints.

The IoT has been used to collect inventory data in a variety of sectors. Also, the IoT does not prescribe the sort of data communicated, and can thus can be used to transfer LCI data in addition to others types. This can be observed in the example of [25], who describe a case of using the IoT in the building sector to capture user behavior during the use stage of the buildings life cycle. All sensor data is structured in building information models which provide an infrastructure to create new information services. This illustrates how the IoT infrastructure can support a variety of services by transferring other types of information alongside the LCI data.

Apart from improved accuracy another reason to integrate the IoT with LCI information systems is its capacity to help overcome the cross-supply chain challenges. It is sometimes required to exchange information across organizations as the production of materials and goods are part of multiple supply chains [38]. Cross-organizational information systems have been proposed to facilitate the collective gathering, sharing and governing of life cycle information. One example is a cloud-based LCA platform [38] applied in a case study of a life cycle assessment of a cotton T-shirt. Another study [24] presents a similar supply chain collaboration model enabling vertical information exchange on various types of costing, including economic and life cycle inventory, in order to both inform customers as well as improve the internal production process. The cited studies provide some evidence for effective (cross) supply chain collaboration but also emphasize the insufficient financial benefits and low incentives for businesses to share LCI data throughout the supply chain.

3 Life Cycle Assessment

LCA is one of several tools designed for assessing all potential environmental impacts of a product or service. Unique to LCA is its comprehensive scope to consider impacts along several dimensions, for example resources, biodiversity, and human health along the entire life cycle of a specific product or service [15]. The LCA method is standardized in the international standard ISO14040 [20]. Other guidelines provide more detailed guidance, aiming for harmonized application in a specific context. Examples are the International Reference Life Cycle Data System (ILCD) Handbook [13] and the Technical Specification for LCA of ICT equipment, networks and services [33]. These standards, as illustrated in Fig. 1, divide an LCA study generally into four essential parts: (1) determination of scope and a goal definition, (2) collection of inventory data, (3) impact assessment, and (4) interpretation of results [20].

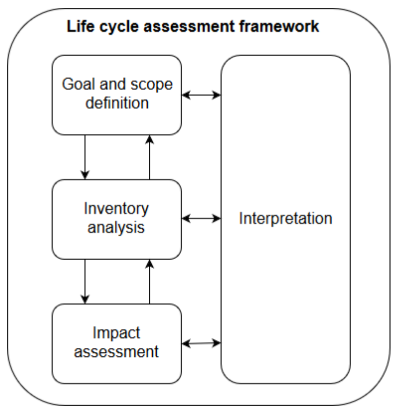


Figure 1: Illustration of LCA stages, derived from [20]

Common to most LCA studies is the objective to assess all major environmental impacts over a product life cycle. By product life cycle, in this paper's context, we are referring to the different states of a product from an environmental point of view [29, p. 7]. Generally, LCA studies use a product life cycle that is divided into four or five successive phases (depending on whether transportation is included or not): (1) extraction of raw materials required for the product, (2) manufacturing the product, (3) transportation of the product, (4) utilization of the product, and (5) end-of-life phase in which the product is reused, disassembled and recycled, or disposed of [20]. LCAs addressing all phases of a product life cycle are called 'cradle-to-grave' analyses. In practice, however, also 'cradle-to-gate' analyses are performed. These analyses are limited to a product life cycle of extraction, manufacturing and transportation.

In our view, one of the major areas of application for the FoT is in the impact calculation of ICT product use. Two major issues have a large impact on the application of the LCA methodology to ICT services. The first challenge is variability of results related to different system boundaries, allocation rules and other limiting definitions [3, 18]. These aspects are typically defined as part of the goal and scope section of LCA studies and associated variability may affect the ability to make valid scenario comparisons. Secondly, the impact calculation is affected by the several methodological challenges of data inventories, the main issue relating to the valid and accurate collection of data [18, 19, 39]. In addition, there might be limitations in data quality, for example, due to a lack of data, wrong data or inaccurate measurements [14]. Both the variability challenges in the goal and scope definition and the issues associated to inventory data collection are of major concern in designing our FoT system. We discuss these in more detail in the forthcoming sections below.

3.1 Challenges in Goal and Scope Definition

Part of the goal and scope of a LCA study is to define the motivation, the application and the intended audience of a study. Furthermore, there is a need to define the system boundaries, the functional unit, the allocation methods and additional assumptions and limitations [20]. These are considered to have a large impact on the reliability of an assessment.

Firstly, a system boundary describes the scope of processes to be included in the analysis of a product system [15]. Specific to digital service assessments are design decisions related to the inclusion of peripheral equipment, the scope with which to represent network infrastructure, and the life cycle phases to include. All such design decisions result in variability of the assessment and thus can affect the ability to make valid comparisons. The study of [3] shows how diverse system boundaries can be used in LCA studies of ICT products and services. Assessments also strongly dependent on the definition of the functional unit. A functional unit is a quantitative measure to which all the calculations of any product system refer [20]. It describes the precise functions of the product system being studied [20]. A functional unit of a digital service could for example be defined as 'browsing a specific web page' or 'watching a video of a given resolution for a specific duration'. Clearly, ambiguous functional units may easily lead to uncertainty in the LCA results. A third and final relevant aspect that may impact the reliability of assessment results is choice in allocation methods. Allocation is a common practice in LCA to apportion inventory data among the functional unit and other services [28]. In that case, input and output material flows are divided according to specific allocation criteria. Several allocation methods exist and LCA guidelines have established an order of preference – or rank. If allocation cannot be avoided the most preferred alternative is to divide flows in proportion to "physical causal relationships" [13].

3.2 Challenges in Life Cycle Inventory Analysis

Life cycle inventory quantifies the relevant input and output material flows of a product system under study. Thereby, inventory data can be obtained either by data collection or data calculation [20]. In [19], LCA studies on digital media are compared regarding their different strategies to obtain inventory data. Two general strategies concerning the collection of inventory data for specific ICT devices are identified: (1) using only existing data sources ("desk-based") or (2) using detailed data for specific cases ("lab-based"). Unsurprisingly, the desk-based LCI collection comes with high uncertainty regarding product components, composition and related material flows, while the lab-based strategy reduces the level of uncertainty. Nevertheless, the manual collection of LCI data faces several other challenges, which are briefly described along the product life cycle.

Resource extraction and product manufacturing: ICT devices consist of many components. The production involves a large number of processes with fast changing materials and product composition. As a consequence, the manual collection of LCI data is very time consuming and can take over months to years. This increases the risk of data uncertainty.

Transportation: Transportation processes can take place during all life cycle stages, e.g. after the manufacturing of a product, or before the final disposal. As the modeling of all transportation processes follows the same approach, all transportation processes can be subsumed. For ICT components and devices, the estimated environmental impact of transportation processes is rather uncertain. In some cases it composes a significant share of the total environmental impact whereas in others it appears to be negligible [3]. The latter can be caused by data gaps, [3] argue further. Environmental impacts from transportation processes may therefore be underestimated. In general, the environmental impacts of transportation highly depends on the transport modality, the distance, the weight and dimensions of the products.

Use phase: As products use comes in different patterns of intensity, the use phase of a product or service is extremely uncertain while it generally a significant part of the environmental impact can be attributed to this phase [3]. Several devices are involved in the usage of a digital service, which can be categorized as (1) data centers, (2) edge and core networks, (3) access networks, and (4) end user devices [28]. Thus, to make a legitimate impact calculation, material flows should be divided among these different components of the device or network based on the agreed allocation method.

End-of-life: The end-of-life phase describes the final treatment, recycling and disposal of products. For ICT devices there is a high degree of uncertainty of what happens with a product at the end-of-life. First of all, there is uncertainty regarding the general meaning of what is considered the final disposal of some of the ICT products [3]. In addition, the knowledge we generally have regarding the final disposal of electronic products is limited in comparison to other types of waste. Many supply chains do not adopt the end-of-life phase of products and the adoption of e-waste management systems to collect such information is still limited. Hence, the information we do have is difficult to access and therefore generally not known to the product manufacturer. Furthermore, e-waste is often exported to countries in the global south, where material and component extraction takes place under manual and informal conditions which also puts a burden to data collection [6].

4 The Footprint of Things

The Footprint of Things is a system wherein a set of distributed, networked sensor and storage nodes, connected trough protocols, are used to store LCI data and make it available for life cycle assessments. Beside the distributed components, its architecture includes a complementary central repository to store average LCI data, thus making it a hybrid system. The distributed nodes are embedded with the products that are part of the supply chain of a product or service and store real-time, specific data for the components. The main role of the central repository is to store global average inventory data about life cycle components and to connect system components across their life cycle phases. At each individual life cycle phase LCI data storage can be either be assigned to the distributed nodes or to the central repository. Depending on the variability in the inventory data during the separate life cycle phases and the required precision of assessment results more or less preference should be given to the distributed nodes over the central repository.

Following this FoT approach the LCA scope becomes independent of the system architecture. This substantially reduces the uncertainty entering LCA studies, in particular related to the definition of system boundaries, functional unit or allocation rules due to the ability of making these LCA decisions independent from the quality of the data. The reduction of uncertainty increases precision and accuracy of study's results and increases the comparability of results. Furthermore, it allows within a life cycle assessment to work more flexibly by integrating the compounded inventory data from different phases of a products life cycle. The FoT approach is able to calculate a partial cradle-to-gate analysis, which covers only extraction, manufacturing and transportation as well as to complete cradle-to-grave analysis, which covers the full product life cycle.

As an example of the FoT approach, we present a conceptual system design for retrieving accurate life cycle inventory data from all devices involved during the usage of a digital service. Our design allows LCI data to become more accurate and provide up-to-date information without considerable delays further on in supply chains. We begin with an illustration of the relation between the FoT mechanism and the distribution of data throughout a product life cycle. Then, we explain how LCI data can be

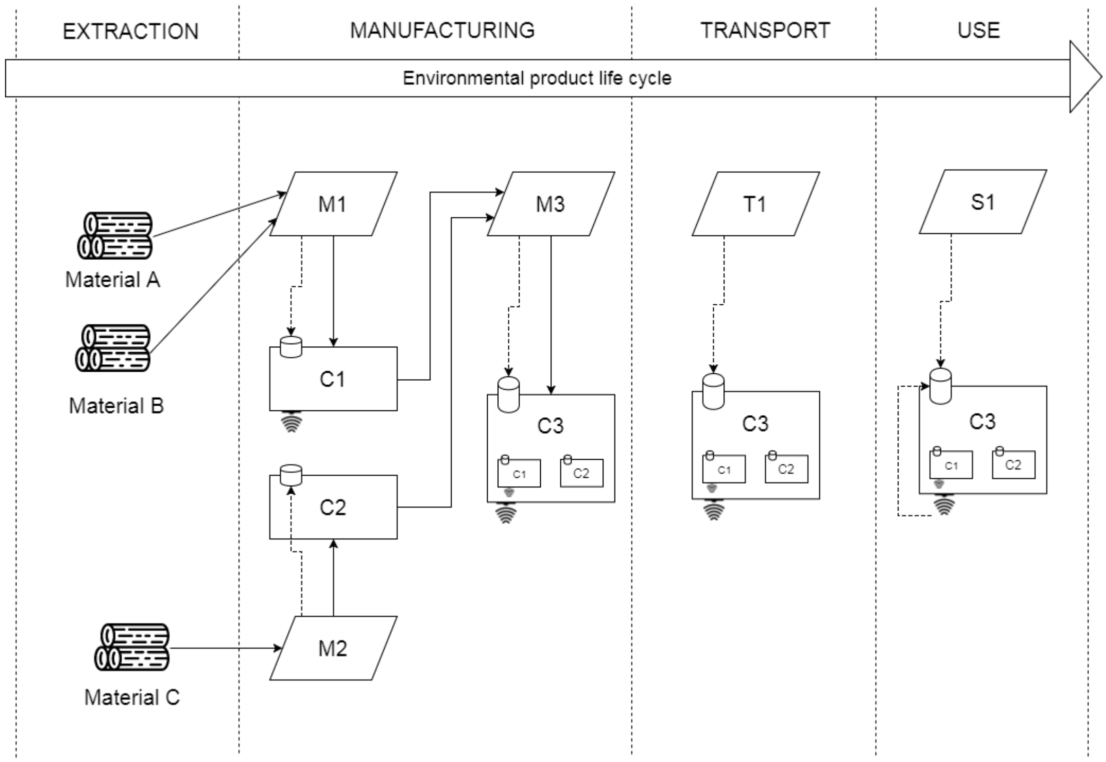


Figure 2: The FoT material and information flows over all stages of a product life cycle.

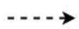
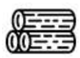
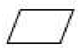
derived using the FoT mechanism to perform an impact calculation. Finally, we show how such an environmental impact calculation works based on the example of making a phone call.

4.1 The FoT Product Life Cycle

The FoT system is intended to be integrated in some or all of the product life cycle phases. Table 1 lists the elements used to describe the FoT architecture. Fig. 2 illustrates the communication flows taking place in the distributed network of the FoT when storing and transmitting LCI data between components and products as part of the various stages of the product life cycle. Our representation includes the stages from the extraction of resources to the use phase of a product. Up until the use phase the product itself can store its specific LCI data. During the end-of-life phase the integrity of the product is likely lost and therefore product LCI data is stored with a central repository. The central repository is not represented in the figure.

In Fig. 2, we use three element types to define the unit of analysis. (1) products, (2) components, and (3) raw materials. Products are composed of components, while components can be composed of other components or raw materials. Two special categories of products being part of a FoT architecture are machines (Machines M1-M3 in Fig. 2) and means of transport (Transportation T1 in Fig. 2). In basic essence, a machine is a device that assembles a product from its components. In the FoT, its role is to store the relevant LCI-data on the assembled component making it a distributed storage node in the FoT architecture. On a more refined abstract level, it becomes apparent that such a machine is itself a product

Table 1: Elements used in the FoT architecture

Icon	Type	Description
	Material flows	A flow describing the state change of product, component or material in the product life cycle.
	Data flows	The flow of life cycle inventory and associated meta-data describing the product, component or material in the product life cycle.
	Materials	The physical natural resource, such as wood, aluminum or silicon, which can be extracted to be used to manufacture a product, and is the root source of information for the LCI (a passive element).
	Product or product-components (the data nodes)	The core elements defining a unit of abstraction that can be considered to become an entity reporting its own LCI accounting (an active element)
	Interacting products (and components)	The products, such as machinery and transport systems, which are used in the product life cycle of another product. Therefore the impact of their operations should be accounted in the LCI of that other product.
	Storage nodes	A unit of hardware embedded in a product or product-component on which LCI data and meta-data can be stored.
	Sensors	A unit of hardware embedded in a product or product-component which enables reporting of LCI data from the storage unit to parent products, interacting products, or central repositories.

or component. Hence, it is depicted as a product with the role of a LCI-data provider. Furthermore, a distinction is made between active and passive elements. Active elements (e.g. Component C3 in Fig. 2), in contrast to passive elements (e.g. Material C in Fig. 2), are self-aware, meaning they contain storage nodes for LCI-data and have the ability to communicate. Additionally, they may be equipped with sensors that can later (during the use phase) collect additional LCI-data. On the other hand, passive elements (e.g. a capacitor on a motherboard of a mobile phone) are generally too small to be equipped with such FoT hardware. Again, the role of the LCI-data providers is to inject LCI-data about passive elements into the data storage nodes of active elements. This process is described in the following in more detail.

The construction of the life cycle inventory usually begins with resource extraction. The environmental impact of the resource extraction is likely to follow from manual assessment and should be made available to the machinery involved in the process of extraction (e.g. Machine M1 in Fig. 2). The next step is to propagate this inventory of resource extraction data forward throughout the supply chain. This requires that during the production and assembly of a product, this newly created product also obtains the LCI-data of the components used to manufacture the product. As a result, data is exchanged between a component (e.g. Component C1 in Fig. 2) and the component that it becomes part of (Component C3). In addition, data is exchanged between the machinery used to manufacture the product (e.g. Machine 2 in Fig. 2) and the component manufactured (Component C3 in Fig. 2). All the received LCI data is written to the storage unit of the new component C3. Optionally sensors are added to a component to collect data about the operational use of a component.

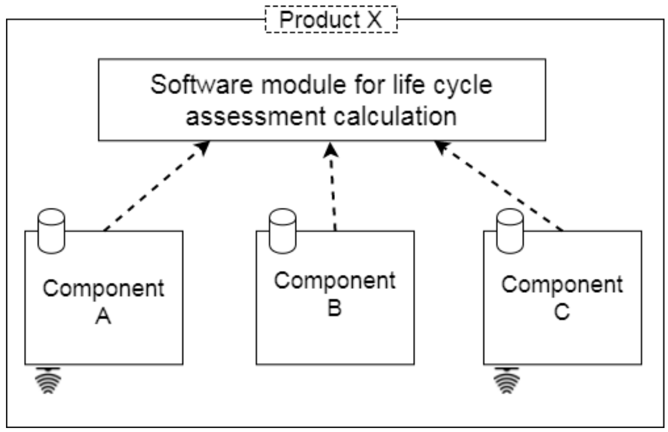


Figure 3: Example composition of a product (partly) equipped with IoT technology (e.g. sensors, storage) to enable the FoT.

4.2 The FoT Impact Calculation

An impact calculation supported trough the FoT addresses mainly the environmental impacts of a product, increasingly disaggregated by service-based use of products. Therefore, an impact calculation of a service in our FoT architecture best takes place in a software module of the product. Fig. 3 illustrates an abstract representation of a product X composed of components A, B, C, and a module for LCA calculation. Each component is equipped with a storage node managing the component's footprint throughout its own life cycle. Inventory data acquired during the production of a component (e.g. Components A, B, and C in Fig. 3) can either be manually collected or derived from the machinery used to manufacture the new component or product. Operational inventory data is collected using direct observations from sensors added to the component (e.g. Components A and C in Fig. 3). Then, a combination of data from the storage node and operational data from sensors is accessed by the LCA software module to create the service-based impact calculation.

The Components A and C, depicted in Fig. 3, are equipped with sensors to measure the environmental flow data during the operational phase of the product (e.g. electricity consumption or greenhouse gas emissions). Consider a battery to be attached with an energy sensor to measure the consumption of electricity. This can provide more accurate information of the energy consumption during the delivery of one service (under the assumption of single service use of the resource). However, all additional sensors and calculations of course increase battery load which negatively affects the environmental impact and product use. Minimizing energy use is thus not only a matter of concern to engineers making LCA to run as a low-energy background process, but also a as a trade-off for the end-user between LCA precision and product performance. Where appropriate data is collected, stored and transferred relative to the duration of a flow such that the functional unit of an assessment can relate to the duration of product use. This could for example involve sharing a components life-expectancy to depreciate the environmental costs of manufacturing over the use of the product. The storage of this type of average data will be facilitated by the central repository.

Our hybrid approach makes use of the advantages of both decentralized and centralized systems. A product (e.g. machines, transport vehicles or individual components) could still partly control data on a central data repository. This opens up two interesting design alternatives: a product may store all relevant LCI-data itself. Or it could simply store references that point to the central data repository. In either case, the centralized data hub can also be seen as a fall-back mechanism. It is, for example,

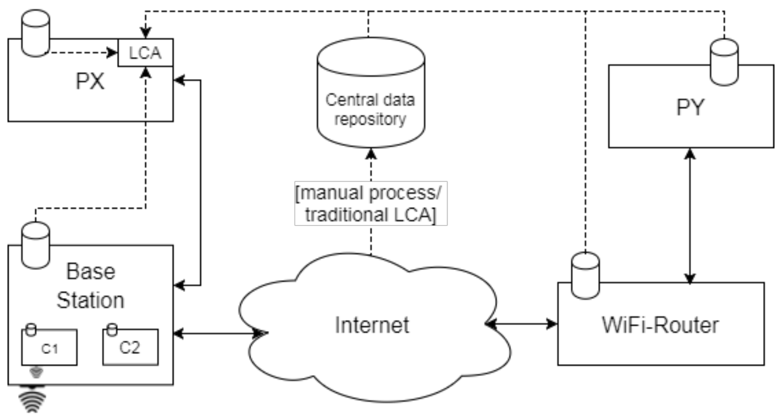


Figure 4: A direct environmental impact calculation of a VOIP call.

conceivable that the FoT is not implemented in all the products that are involved in the delivery of a digital service. In this case, an automatized LCA could use generic data provided in the central data repository.

4.3 The FoT in a Voice over Internet Protocol call

Fig. 4 illustrates the potential use of the FoT through a simplified example of a VoIP phone call. Phone PX and PY are connected via mobile Internet. Phone PX initiates a VoIP call with Phone PY. Phone PY receives the call through a local Wifi network. The LCA software module on Phone PX performs and environmental impact calculation. The example shows the difficulty of resource allocation in situations where various components play a role by showing all the required information flows. Futhermore, Fig. 4 demonstrates the application of the FoT as a hybrid mechanism to communicate all relevant LCI data for an impact calculation of a service (e.g. a VOIP call).

5 Discussion

The FoT allows an LCI process to become more accurate and timely by attaching information about a product's environmental impact to the product itself. The design considerations for this FoT architecture require evaluation. Therefore, we discuss the contributions of the FoT to LCA practices. In particular, from a technical perspective to evaluate the arguments why we consider a hybrid approach best fitting for leveraging the potential of the IoT for LCA data collection. In addition, we provide a perspective on the social and political challenges which we foresee to play an important role making the FoT viable.

5.1 Implications to LCA

Ongoing developments towards connected production and industries (Smart Factories, Industry 4.0, Industrial Internet of Things) push forward for new mechanisms that automate the LCI production processes, therefore creating future prospect for the viability of an automated FoT system. The FoT design impacts the way how LCA studies can be performed. The design of the FoT system overcomes some of the current challenges in the LCA methodology. In terms of the LCI data collection, automatic reporting on the life cycle phases of ICT devices contributes by providing improved data quality. In addition, the

FoT concept may tackle variability in study design and can contribute to overall comparability of results. However, it should be considered that not always all flows associated with the product life cycle can be automatically tracked. Chiefly, these are flows that come after the use phase (e.g. End-of-Life phase) or processes that are not automated (e.g. extraction of resources). For these processes, when using the FoT, one may manually (or semi-automatically) inject LCI-data during the manufacturing phase by using the central repository service. The LCI data acquired during the production may also contribute to increasing supply chain transparency [8] and enable better predictive maintenance [11]. Both transparency and predictive maintenance are key arguments for establishing sustainable productions processes [8].

Still, there remain technical issues to consider: the automatic impact calculation requires integration of context information that might not be available to the component yet. For example, the impact created in upstream phases needs to be allocated and reported during the use phase. The most common approach is just to assign a proportion of the total impact of a product. But to include such inventory in the impact calculation, it requires to use average LCI data as the life-expectancy of a product-instance is typically unknown, or has a high uncertainty in its first use. Another issue would be to acquire information about the composition of consumed energy sources. While it is conceivable that a component tracks its energy consumption, it cannot know whether the energy stems from renewable or fossil sources, which affects the environmental impact outcomes. For both examples, our hybrid approach opens pathways to flexible solutions: it allows for a central repository providing generic data from which the average expected lifetime of a component could be calculated. One could even think of a system design, where a product is disassembled by a machine at end-of-life that in turn reports back to the central repository, updating this calculation. Furthermore, to include the energy composition in a calculation, the central repository could register location-based data on the energy composition to be accessed when making LCA calculations. Another challenge is the appropriate allocation of inventory data, as a product will in most cases not only provide a function to the specific assessed functional unit. Most of these technical issues are not only specific to the FoT, but also to LCA in general.

5.2 Technical Considerations

As we have seen, the FoT approach allows to tackle some LCA-specific challenges. However, why should we consider a hybrid approach over a centralized? A hybrid approach has a number of advantages over a centralized distribution mechanism. Firstly, locality of LCI data sidesteps the complexity of a unified, multi-vendor LCI system and enables a gradual introduction. This provides the flexibility for a stepwise adoption in the industry. Secondly, locality of information allows for local assessment that bypass the cloud. The benefit is that we allow a more nuanced and flexible adoption of LCA for manufacturers or service operators that are concerned with making information public (we discuss the issue of information disclosure in more detail below). This local assessments can be made secure and private.

Our proposed bottom-up mechanism also has some potential consequences, drawbacks and limitations. Firstly, a designer is confronted with a decision what FoT infrastructure to implement and integrate during product development. There is also a need to define the granularity of a component, determining the physical elements which together form a component. For example, the capacitor, microprocessor, and battery on the circuit-board together form a network-card, which itself is a component of a mobile phone. Then, a designer needs to decide on what components should become active (LCI data provided by means of the FoT) or passive (LCI data provided through traditional means). Moreover, the trade-off must be made to equip components with sensors and storage, specifically with respect to the potential overhead these may create in terms of energy usage and resource usage. A good rule of thumb might be to add FoT-capability in components that already (partly) provide computational infrastructure (e.g. sensor, storage, networks). Furthermore, a potential disadvantage of the approach is that local replication of LCI data within product components can lead to inefficiencies. As many components of the same type will share LCI-characteristics (e.g. data about resource extraction and manufacturing phase), there would be a lot of redundant data stored on the components. A central data repository could help to avoid this through representation of the average flow data that can be supplemented by specific data if necessary.

Concluding, we see the necessity for a hybrid approach where, in principle, a component is responsible to report on its environmental impact, but the provision of data is supported by a central repository that provides generic and non-redundant data. Nonetheless, there is a need to further investigate more detailed the design alternatives within this architecture, depending on practical use cases.

5.3 Social Considerations

The idea behind the FoT is to build upon established IoT infrastructure to facilitate data collection in LCI data. Therefore, it is dependent on the feasibility and dissemination of IoT technology. Challenges to these systems are also likely to impact the FoT mechanism. As the IoT is an emerging paradigm [9] it is inherently associated with several challenges [37]. Most challenges identified in the IoT literature discuss technological limitations of the current Internet architecture and management of heterogeneity, in particular the added network traffic as a result of the IoT [7]. Others relate to social and political questions, as discussed by [23]. Most important in our opinion is the issue of security, privacy and trust [7, 23], which raises both technological and social questions. The implication for our proposed FoT approach is that it creates an overhead of collection, transfer and storage of data. In addition, LCI-data can be considered sensitive and would require a set of data protection measures.

A first concern prevails during the first three life cycle phases, being extraction, manufacturing and transportation. Considering our VoIP-Call example illustrated in the previous section, the collection of LCI data (e.g. the energy required to produce the phone's components) may be hindered by the phone manufacturer's willingness to publicly share any (LCI) information about its suppliers. Even though more firms began to provide more transparency of their supply chain, many are still reluctant due to the fear of losing competitive advantages by disclosing their suppliers [12]. Still, an upcoming trend among some larger enterprises is to disclose their suppliers, as well as smelters and refiners (e.g. [2]). We also expect future governmental policies to strengthen this trend, by enforcing manufacturers to provide more information about their supply chain. As an example we point to the EU CSR-Directive which has recently been implemented in German law [10].

Additionally, there is a strong need to ensure the integrity of the data that is shared along the product life cycle. There exist promising approaches to address this issue in supply chain transparency using blockchain technology [27]. This application of blockchain technology is already in use to track sustainability in food supply chains [34], and could authenticate inventory data collected by the FoT. Again referring to our VoIP-call example, the data about the components of a phone (e.g. screen, battery, casing) and their sustainability characteristics could be stored in the blockchain to ensure their integrity along the supply chain. However, even with a mechanism to ensure data integrity in place, it remains an open question, how to verify claims that are made about any property of a component or material.

The third concern considers the additional privacy-related risk for devices tracking and revealing personal data. A user should be protected from the forces driving them to share sensitive data, such as energy usage patterns or the date and time of service usage. This might be necessary in our VoIP-example for the user of phone PY. The user might be required to send possibly sensitive data to phone PX, where the impact calculation takes place. Even if we consider any organization participating in the FoT as trustworthy, data could be revealed to third parties in the case of data breaches. Therefore, an implementation of the FoT needs to consider the trade-off between accuracy of LCI data and personal privacy and make use of countermeasures like anonymization, pseudonymization or aggregation where appropriate. Following the principles of privacy-by-design, the participation in the FoT would be opt-in for any end-user device. An advanced design could then also allow a user to configure her or his privacy preferences, i.e. the level of detail of the shared data.

6 Conclusions and Future Work

This paper addresses the problem of collecting accurate and precise inventory data for the environmental impact assessment of a service on ICT hardware. While most designs in the literature rely on a centralized approach, this paper presents an alternative way to collect and communicate life cycle inventory data based on the infrastructure of the Internet of Things. The study contributes a novel hybrid design, "the Footprint of Things", that considers a decentralized bottom-up approach as the baseline to communicate inventory data throughout the product life cycle. We presented the vision and outline of a hybrid architecture that reduces the coordination complexities for the involved actors across supply chains while it enables real-time and more precise impact calculation of ICT services. We expect this to be helpful to design direct feedback systems to inform users about the environmental impact of service usage. We found that challenges applicable in the Internet of Things, seem to apply well to the concept of Footprint of Things. Reflecting on our design, the most important challenges are for one hand privacy concerns of service users or data considered sensitive by firms. In the future, we plan to develop a working prototype of the FoT based on the architecture presented in this paper, in order to evaluate its potential in a real world setting.

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