Product Carbon Footprint and Life Cycle Assessment of ICT – Literature Review and State of the Art

Daniel Grimm
TU Berlin, Germany
d.grimm@tu-berlin.de

Daniel Weiss
TU Berlin, Germany
d.n.weiss@gmx.de

Koray Erek
TU Berlin, Germany
koray.erek@tu-berlin.de

Ruediger Zarnekow
TU Berlin, Germany
ruediger.zarnekow@tu-berlin.de

Abstract

The concepts of Life Cycle Assessment (LCA) and Carbon Footprint (CF) represent powerful tools in aiding towards the reduction of an organization's environmental impacts. Because of the influence of information and communication technology (ICT) on worldwide environmental impacts, these concepts are particularly significant in this field and receive growing interest. Surprisingly, literature constitutes ICT-related LCAs to be strongly affected by uncertainty as well as comparability and validity issues. This contribution aims at clarifying the status quo of ICT-related LCAs by providing a literature review of existing studies. The review reveals and discusses the current situation, displays evidently accepted standards and methodologies as well as similarities within the studies and finally points out research gaps.

1. Introduction

Climate Change and global warming represent significant challenges of the 21st century. Since there is consensus that greenhouse gases (GHGs) are the major cause of climate change, organizations are increasingly faced with the task of quantifying and ultimately reducing the amount of GHGs that are emitted through their activities, products and services. Lately, the concepts of Carbon Footprint (CF) and its origin Life Cycle Assessment (LCA) have seen a massive rise in interest, usage and research [1]. LCA represents a "cradle to grave" approach that can be used to assess various environmental impacts on a very detailed level for every life cycle phase of a product [2]. Various LCA methodologies and standards have emerged (e.g. ISO 14040/44 [3], PAS 2050 [4], GHG Protocol [5]) and in addition there is a wide range of databases that can be consulted when conducting LCAs (e.g. Ecoinvent, BUWAL, MIET). Furthermore, a high level of complexity and pressing issues such as uncertainty and variability of results [6] often lead to ambiguity and confusion in users and recipients alike. This holds especially true for information and communication technology (ICT) products and services, which is due to the complexity of the involved electronic and electric components and the widespread supply chains. Over the last two decades, ICT-related LCA research has steadily increased and has yielded various approaches, studies and methodologies focusing on a wide range of subjects.

Uncertainty and validity issues as well as a lack of comparability between studies are reoccurring themes within the existing literature on ICT LCA [7]. This is a result of the different methodologies and databases used but also because of the many assumptions needed to perform an ICT LCA. This contribution seeks to show the de-facto standards, preferred methodologies and assumptions as well as derive lessons learned and show current trends in order to bring more clarity and certainty into this field. Therefore the paper will address the following research questions:

- *Q1. How can analyzed subjects of ICT LCA and CF studies be structured?*
- *Q2. What are preferred standards, methodologies and scopes of LCA and CF studies focusing on ICT subjects?*
- *Q3. Which future research directions can be drawn from this for the field of ICT LCAs?*

Thereby the paper is structured as follows: Following this brief introduction, section 2 presents an approach to classify subjects of ICT LCA and CF studies in order to answer Q1. Section 3 displays the research methodology that was used to conduct a literature review on ICT related LCA and CF studies. Aligned with the research methodology, section 4 presents categorized results of the literature search following the introduced classification approach in section 2 and assesses the status quo of ICT-related LCA and CF research. Based on the literature review, section 5 highlights identified research gaps and gives an outlook on future work in the field of ICT related LCAs and CFs, primarily addressing Q3. Finally conclusions will be drawn.

978-1-4799-2504-9/14 $31.00 © 2014 IEEE
DOI 10.1109/HICSS.2014.116

2. Subjects of ICT related LCA and CF

By operating ICT infrastructure (e.g. server, local area network (LAN) and storage systems) as well as supportive systems (e.g. cooling and power supply) in datacenters, IT-Service providers are able to produce IT-Services. Users consume them as needed by means of workplace environment hardware (e.g. laptops, desktops and monitors). Network infrastructure components (e.g. router and switches) are needed to transfer IT-Service related data over the Internet or LAN, which can be perceived as the distribution of IT-Services. Considering this situation, we developed a classification approach (see Figure 1) that distinguishes between LCA and CF studies focusing on workplace environment, data center, networks or IT-Services.

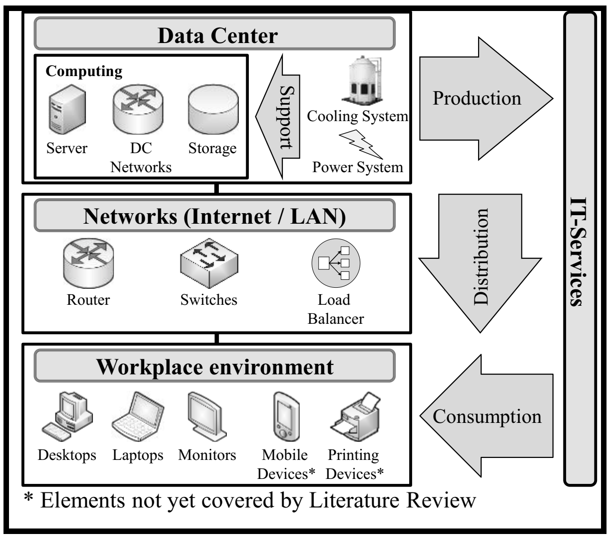

Figure 1: Classified Subjects of ICT LCA and CF

3. Research methodology

A literature review is accepted as a central research method to prevent redundant reinvestigations while simultaneously using the existing knowledge base to enhance research rigor [8]. [9] see a literature review as "[…] the foundation for research in IS" and underline the significance thereof for promoting IS research. In order to ensure scientific rigor and validity, this contribution is geared to the framework for literature reviews proposed by [8] and depicted in Figure 2.

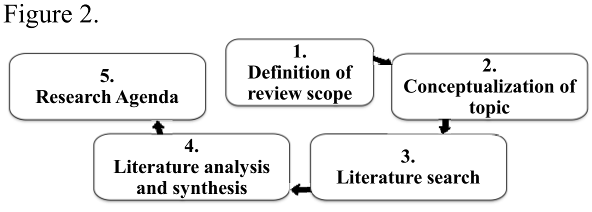

Figure 2: Framework for literature research [8]

3.1 Definition of review scope

In accordance with the framework, this contribution applies Cooper's taxonomy for literature reviews in order to define the scope of the review [10]. The highlighted areas in Table 1 show the scope that was determined for this literature review:

Table 1: Taxonomy of literature review [10]

Charac-teristics	Category			
Focus	Research outcomes	Research methods	Theories	Appli-cations
Goal	Integration	Criticism		Central issues
Organi-zation	Historical	Conceptual		Methodological
Perspective	Neutral presentation		Espousal of position	
Audience	Specialized scholars	General scholars	Practitioners/ Politicians	General public
Coverage	Exhaustive	Exhaustive and selective	Representa-tive	Central/ Pivotal

3.2 Conceptualization of topic

The framework now advises authors to provide working definitions of key terms and a general overview of the surrounding issues.

Life cycle assessment is a method to assess the environmental impact of a product or service throughout its entire life cycle and can be applied to a wide range of objects. The International Organization for Standardization (ISO) accredits LCAs through the ISO 14000 series and defines them as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [11]. LCAs are divided into the four stages goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation. Additionally, the literature differentiates between two LCA approaches, the bottom-up approach or process analysis (PA) (emission sources are split into categories to simplify quantification) and the input-output analysis (IO), where the economic input-output (EIO) model is adapted to fit into the context [2]. Lately, a hybrid approach has gained in momentum, trying to perform a more holistic analysis by addressing several disadvantages of the previous approaches. Furthermore, two LCA methods can be distinguished, the attributional method determines "[…] the environmentally relevant physical flows to and from a life cycle and its subsystems" whereas the consequential method determines the changes in these flows due to potential changes [12]. While the ISO 14000 series appears to be the dominating standard in LCA [13], a range of additional standards has emerged that are mostly heavily built on the ISO but vary on several issues. Important industry independent standards include the Publicly Available Specification (PAS): 2050 [4], the GHG Protocol [5] and the ILCD Handbook [14] in addition to the specifically ICT-industry standard by the International Telecommunication Union (ITU) [15].

The *Product Carbon Footprint* refers to the quantification of GHG emissions and removals on the product level through a LCA, usually expressed as metric tons of CO_2 equivalents (CO_2e) [1]. A PCF therefore represents a LCA with a limited focus on climate change of a product and consequently, LCA methodologies and application principles should be employed. Because of the interrelation and analogy of LCA and PCF, we decided to conduct a literature review covering both of the subjects.

3.3 Literature search

The actual search for the literature naturally is the centerpiece of the framework and a total of 4 databases (IEEE Xplore, ScienceDirect, EbscoHost - Business Source Complete, ProQuest), 6 conferences and 70 journals were searched using the keywords *life cycle assessment* respectively *carbon footprint* in combination with "*IT*", "*ICT*", "*data center*", "*server*", "*IT services*", "*network*", "*personal computer*" and "*laptop*". Despite the authors' references to ICT, the field of mobile phones will be left out of the literature review. The contribution focuses on stationary and infrastructural ICT and furthermore, there are already existing literature reviews about mobile phones, which cover that field excellently [16].

The selection of the journals was based on the "Association for Information Systems (AIS)" journal-ranking, where a maximum average rank point (ARP) of 30 over the period between Jan 1995 – Apr 2013 was used as the selection criteria. Given the goals, the *International Journal of Life Cycle Assessment* was also included. In order to filter out relevant articles, title and abstract were analyzed for hits and consequently only relevant journals were counted. Searching the selected journals and conferences yielded 15 respectively 0 results. The databases were sorted for relevance, the first 100 hits were screened and only additional contributions (34) were counted. Lastly, as recommended by the literature [8, 10] further forward and backward searches were conducted, yielding another 57 relevant results and therefore a total of 106 results However, after a more detailed analyzes of the results only 98 were ultimately deemed relevant and included in the review.

4. Literature analyzes and synthesis

As explained in chapter 2, the results were categorized into four groups, which are presented in the following sections. The most significant findings are illustrated in a table for each group. The grey-marked cells within the tables imply that the analyzed study (row) deals with the specified issue (column).

4.1 Workplace environment hardware

After analyzing the total findings, 36 contributions were categorized into the workplace environment hardware group as summarized in Table 2. There are several immediate conclusions one can draw from the table alone, which are strengthened and expanded through a thorough analysis of the findings.

Beginning with the structure and approaches taken, one has to state that the scope of differences (regarding all aspects) is far wider than one would anticipate in a field that has seen several decades of research. There rarely are studies with the same determinants. We could only identify 12 studies that explicitly conduct a full LCA, i.e. from extraction of the material the end-of-life (EoL). The rest left out at least one phase or specifically concentrated on a single phase to emphasis its importance. This hold especially true for the EoL phase, many authors put a strong focus on this particular phase. This is due to its importance towards the direct environmental impact of the investigated products and the potential positive effects adequate recycling can have. Additionally, only a minority (9 studies) broke down the results on a component level and an even smaller number of researchers (5 studies) looked at the same products in different regions, emphasizing the regional differences. Similar diverging results are observable for the components; eight studies investigated a PC, a monitor and input components, whereas the majority focused on monitors. 25 studies examine monitors or PC and monitors in combination; PCs were investigated in 22 cases, laptops in 13. Especially diverse is the choice of examined environmental impacts, some studies concentrated on a single impact whereas other studies tried to analyze more than 20 different impacts (we had to summarize several impacts in order to maintain a certain level of clarity).

As for the choice of standard, the ISO family appears to be the favorite choice. 10 studies explicitly stated that they were following the ISO standard. Furthermore, the influence of the ISO on the structure and procedure was often visible but the standard not named specifically. Other standards were only named sporadically, the GWP 100 twice, the Ecological Footprint also twice and the PAS:2050 once. However, mostly no specific standard was mentioned when explaining the studies' approaches (22 times).

Furthermore, the ISO leaves a certain freedom to the authors as some steps in its process are only optional. There have been some very detailed studies that show the importance of these and similar issues such as weighing, uncertainty, data corrections [17, 18, 6] and the significant influences they can have on results.

The methodology to calculate the environmental impacts again shows serious discrepancies. The Eco-Indicator 99' methodology most named most often (8 times), followed by SIMAPRO (6 times). Apart from that there are again several methodologies that are sporadically used such as Swiss Ecopoint (one mention), cost-benefits analyses (one mention) or the CML method (one mention). The majority of studies however, again follows own methods or methods that adjacent to accepted methods but deviate on certain issues.

The real discrepancies however, are visible through the various assumptions that were made throughout the studies. The assumed lifetime of a product (one of the most influential aspects) ranged from 2-6 years, the majority of studies however chose a lifetime around 4 years. The assumed usage time also shows great differences, in length (rang of 3-8 hours) and detail, i.e. office versus home usage ratios, if considered at all. In addition to these crucial assumptions, the studies show a wide range of assumptions the authors deemed necessary to include. Some authors included recycling or reuse rates, cost distributions as well as fuel conversion factors and hours of idle/sleep modes, to name but a few. Many authors did also not measure the power consumption of the components but assumed values or referred to other studies for exact numbers. The range and number of different assumptions did not make it possible for us to name them individually but we want to emphasize that a plethora of assumption was made, each naturally influencing the result of a study. Due to the many assumed values, LCA studies often illuminate very specific settings. Thus, the main issue on further ICT LCA research would be the identification of general drivers through sensitivity analyses of input variables.

It is also often pointed out by authors that acquiring recent and detailed data is very difficult [19–21]. This can be due to several reasons, often authors refer to the fact that manufacturers and/or suppliers are not willing to share sensitive information or that to measure and assess every component of the study is out of scope. The lack of adequate data however, is extremely alarming when keeping in mind that most studies follow modeling based approaches were the data is absolutely crucial for precise and relevant results.

Similar, but not as grave issues arise when it comes to the exact components involved. Many authors specifically name e.g. processor type, hard drive type, etc. but there are also many cases where the authors used "a standard PC" or similar terms, naturally diminishing the chance to fully compare and comprehend the results.

Another noticeable fact is that many studies were conducted or supported by hardware manufacturers themselves [e.g. 22–25].

However, despite the various differences many strong conclusions can be drawn from the findings. Most authors agree that the use phase appears to have the strongest influence on the environmental impact for the investigated components; roughly 2/3 can be contributed to it (expressed in CO_2e). The production phase is the second most influential one, with around 20% - 30% of environmental impact being caused in this phase. The rest of the phases appear to be marginal for most of the assessed impacts (keeping in mind EoL's special role). This at least holds true for CO_2e. However, there are also various studies that show varying results (especially ones not concentrating on CO_2e), e.g. [26] conducted a PC LCA and concluded that the pre-manufacturing stage has the greatest impact for nearly all the impacts they assessed or [17] found that the manufacturing stage has the biggest influence on the lifetime energy of a laptop**.** A generalization of results therefore is difficult because of the many discrepancies explained earlier

The EoL treatment is pointed out as particularly significant when it comes to measures of decreasing environmental impact that directly causes harm to humans. This is mainly due to many electronic and electric components that are part of the devices and the resulting complexity of adequate recycling, reuse or disposal.

The variation of results is alarming, which is why various authors point out these and similar issues such as a lack of comparability, inconsistencies and the usage of different standards and methodologies [e.g. 26, 6]. The variations and inconsistencies have diverse reasons but a few major aspects could be identified. As shown above, there is no real agreement about what standard or methodology to use. There are multiple approaches that differ in used calculation methods, assessed components, included impacts, cut-off rules, weighing, error correction and many more. Additionally, assumptions about life span, usage time and similar issues vary greatly, naturally leading to great variations in the results. Chosen energy mixes and power consumptions (measured or not) of devices further lead to great discrepancies in results. An adequate comparison of studies is therefore often impossible. Resulting from the wide range of assessed impacts, methodologies, standards, assumptions, etc. the findings regarding the distribution of impacts among the phases need to be processed with caution.

Table 2: Workplace Environment Hardware Findings

Source	Assessed Impact Categories													Components				Life Cycle Scope					Presentation of Results		
	GHG emissions	Ozone depletion	Air emission/quality	Landfill space	Soil quality	Water emission7quality	Acidification	Eutrophication	Resource use	Lifetime energy use	Radioactivity	Health effects	Toxicity	PC	Laptop	Monitor	Mouse & Keyboard	Extraction	Production	Distribution	Usage	End of life	Per Phase	Per Component	Per Region
[27]	■		■	■		■			■							■						■	■		
[28]	■		■	■	■	■	■	■	■					■	■	■			■	■	■	■	■	■	
[29]	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	
[30]			■	■	■	■			■					■		■	■					■	■		
[31]	■			■					■					■	■	■	■	■	■	■	■	■	■		
[19]	■	■	■	■	■		■	■	■			■	■			■			■		■	■	■		
[32]	■	■	■	■	■	■	■	■	■	■	■	■	■			■		■	■	■		■	■		
[22]	■														■			■	■			■	■		
[33]												■				■						■	■		
[34]											■			■		■			■		■	■	■		
[35]											■			■		■			■		■		■		
[36]	■	■	■	■	■		■	■	■			■	■	■	■	■	■	■	■	■	■	■	■		
[37]	■									■				■		■			■		■	■	■		
[38]	■	■	■	■	■	■	■	■	■		■	■	■			■		■	■		■	■	■		
[39]									■						■		■	■				■	■		
[40, 41]										■				■					■		■		■		
[26]	■	■	■				■	■	■			■	■	■				■	■	■	■	■	■		
[42]	■	■	■			■	■	■	■			■	■		■							■	■	■	
[43]	■		■				■	■	■			■	■	■		■	■	■	■	■	■	■	■	■	■
[44]	■	■	■			■	■			■				■	■	■	■		■	■	■	■	■		
[18]	■	■	■	■	■	■	■	■	■		■	■	■			■		■	■	■	■	■	■		
[45]	■															■			■	■	■	■	■	■	
[46]	■			■					■					■	■	■	■				■	■	■		
[20]	■	■	■			■	■	■	■	■		■	■	■		■	■	■	■	■	■	■	■	■	■
[47]	■															■			■	■	■	■	■		
[48]			■		■	■			■	■		■		■	■			■	■	■	■	■	■		
[49]									■					■	■							■	■		
[23]	■														■				■	■	■	■	■	■	■
[50]										■				■	■	■		■	■		■	■	■		
[24]	■														■			■	■	■	■	■	■		■
[25]	■													■				■	■	■	■	■	■		■
[21]	■													■		■	■	■	■	■	■	■	■		
[17]	■								■	■					■		■			■			■		
[51]	■	■	■			■	■	■	■	■		■	■	■		■	■	■	■	■	■	■	■	■	
[52]				■			■		■			■		■		■	■	■	■	■	■	■	■		
[53]	■	■	■	■	■	■	■	■	■	■				■		■	■	■	■	■	■	■	■		

4.2 Data Center

A total of 22 studies could be found for this group, 15 for data centers and 7 for server (see Table 3). The life cycle for data center was categorized into (full and partial) embedded, operational and infrastructure. This is following the structure that the majority of studies for this group chose. Embedded hereby represents the energy necessary to make a product [54]. The assessed impacts were categorized according to the Eco-Indicator methodology. The Literature search revealed that servers are the most influencing components in data center which is why the studies concerning servers are presented separately in Table 3. LCA and CF studies focusing on data center components show several similarities to the group of workplace environment hardware. The use phase is also perceived as the most significant contributor towards environmental impacts. Because of the usage patterns of data centers, the share is even higher. Most studies suggest that roughly 90% of CO_2e emissions for data centers are emitted during the use phase. Especially for servers, similar issues revolving around inconsistencies, lack of comparability and agreement about standards and methodologies arise. However, since the devices are not as diverse and many studies show similar focuses and scopes, the discrepancies are not as grave as for workplace environment hardware. The studies show that the assumed energy mix heavily influences the total environmental impact. The Fujitsu studies for example showed a nearly 400% increase in the CO_2e result for identical products in two different countries [55].

Table 3: Datacenter and Server Findings

Focus	Source	Assessed Impact Categories: Human Health (DALY)				Ecosystem Quality				Resource damage			Other			Components			Life Cycle Scope				Presentation of Results		
		Carcinogens	Respiratory organics	Respiratory inorganics	Climate Change	Ozone depletion	Eco toxicity	Acidification	Eutrophication	Landfill space	Fossil Fuels	Nuclear fuel	Water	GHG emissions	Exergy consumption	Computing	Power	Cooling	Full Embedded	Partial Embedded	Operational	Infrastructure	Per Phase	Per Component	Per Region
Whole Data Center	[56]	■	■	■	■	■	■	■	■	■	■	■	■			■		■			■		■		
	[57]	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■			■		■		■
	[58]													■		■	■	■			■	■			
	[59]												■	■	■	■	■	■	■		■	■			
	[60]													■	■		■		■			■	■	■	
	[61]																			■					
	[62]													■	■	■	■	■	■		■	■	■	■	
	[63]													■		■	■	■			■		■		
	[64]										■					■	■	■		■	■	■	■	■	
	[65]													■		■					■		■		
	[66]														■		■			■	■	■			
	[67]														■		■	■		■	■	■			
	[68]													■		■	■	■	■	■	■	■			
	[69]	■	■	■	■	■	■	■	■	■				■		■	■	■	■	■	■	■	■	■	
	[70]	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	

Focus	Source	Carcinogens	Respiratory organics	Respiratory inorganics	Climate Change	Ozone depletion	Eco toxicity	Acidification	Eutrophication	Landfill space	Fossil Fuels	Nuclear fuel	Water	GHG emissions	Exergy consumption	Server	Cooling	Power	Extraction	Production	Distribution	Usage	Usage (Cooling)	End of life	Per Phase	Per Component	Per Region
Server	[71]													■		■	■	■		■		■					
	[45]													■		■				■	■	■		■	■	■	
	[54] [73]														■	■	■	■	■	■	■	■	■	■	■	■	
	[72]														■	■			■	■	■	■		■	■	■	
	[55]						■	■	■					■	■	■			■	■	■	■		■	■		■
	[74]													■	■	■				■	■	■		■	■		

As in the previous group, many data center studies have also been supported by hardware manufacturers [55, 54]. Furthermore, the discrepancies about which environmental impacts to assess are by far not as big as in the previous group. On the contrary, there appears to be a very strong tendency to express the environmental impact of data centers and/server either as lifetime exergy consumption and/or CO2e.

4.3 Networks

This investigated group shows the lowest amount of research. Only 7 studies could be found that focus on either parts of a network or entire networks (see Table 4).

Since there are so few results that focus on very different devices with varying scopes (i.e. 5 studies investigated individual network devices, whereas the other 2 studies focused on entire or partial networks), it is difficult to generalize results. The databases used were diverse (once BUWAL, once Ecoinvent, twice a database developed by Chalmers University of Technology, once MIET database) and a standard was only mentioned once (ISO). Assessment methodologies show a similar picture, the CML method was used once, the input-output approach was used once and [75] used EPS, EDIP and Eco-Indicator, apart from that the authors did not mention specific methodologies but explained their procedure individually. Because there are so few contributions to this field, we can present some findings a little more detailed than in the groups before. [76] found that, naturally, the impact of the manufacturing phase expressed as lifetime energy use for a Wi-Fi access point in percent decreases with increasing lifetime (69.6%, 53.3% and 43.2% for 1, 2 respectively 3 years), shifting the environmental impact towards the use phase. In a similar study, this time investigating Wi-Fi and Ethernet, [75] found for Wi-Fi 61,9%, 44,9% and 35.2% for 1,2 respectively 3 years and for Ethernet 80.1%, 66.8% and 57.2% during the manufacturing phase. Surprisingly, the CO2e emissions during manufacturing only accounted for 38.1%, 23.5% and 17.0% for Wi-Fi as well as 49.2%, 32.6% and 24.4% for Ethernet, showing the differences in ratios when assessing different impacts. [77] looked at data center network switches and found that the operation caused between 65%-67% of total lifetime energy use. Additionally, their results suggest that the more switches there are the larger the contribution of the manufacturing phase becomes, shrinking the use phase to 52% in the investigated case. In total they found that the networking infrastructure causes between 3%-10% of a data centers lifecycle energy use. [78] tackled the biggest network there is, the Internet. Differentiating between core, metro and access networks, they estimate that the Internet in Australia currently causes 81 kg CO_2-e per-year per-subscriber.

Lifetime energy use and CO2e emissions are the preferred metrics when expressing the environmental impact of network and network devices.

Table 4: Networks Findings

Source	Assessed Impact Categories							Components										Life Cycle Scope					Presentation of Results		
	GHG	Ozone depletion	Water	Acidification	Eutrophication	Resource use	Lifetime energy use	Modem	Switch	Data center switch	Router	Control unit	Core network	Metro network	Access network	Wi-Fi Access Point	Ethernet Access Point	Extraction	Manufacturing	Distribution	Usage	End of Life	Per phase	Per component	Per region
[79]	x	x	x	x	x							x											x	x	
[71]	x								x		x	x							x		x		x	x	
[78]	x												x	x	x						x			x	
[77]						x				x									x		x		x	x	
[76]						x										x		x	x	x	x		x	x	
[80]						x												x	x	x	x	x		x	
[75]	x					x										x	x	x	x	x	x		x	x	

4.4 IT-Services

There were 33 contributions that could be categorized as IT-Services related LCAs (see Table 5). The table shows the groups that the findings could be categorized into whereas the music group investigated issues revolving around digital music, the print group investigated the environmental impact of various electronic reading methods or the change from regular invoicing to electronic invoicing and the movie group looked at movie rentals. In addition to that, one study focused on the distribution of garments in China and one study investigated the environmental impact caused by send an e-mail.

Looking at the used methodologies and databases first, great variations again come into play. 4 studies used a screening LCA, another 4 studies an EIO-LCA, 3 studies mentioned a traditional or regular LCA, the ISO was mentioned twice in addition to that, one mention of a hybrid LCA, one usage of the MIPS methodology, one LCA methodology developed by Ericsson, the CML methodology was also used once and the three studies by Kitou et al. used a methodology developed solely for telecommuting. The rest of the studies (13) used own methodologies. The databases show a similar picture, Ecoinvent was used 3 times, the Easy-LCA database also twice, followed by several databases that were only used once (Ecotax 02, LCASupport, IMPACT 2002+). The rest of the studies used a multitude of other sources such as governmental data, other studies, industry data, census data, etc. This is very comprehendible, due to the nature of the studies that often involved many different fields of investigation (e.g. buildings, transportation, ICT, packaging, recycling all in a single study). It is difficult to find databases that have all the necessary data. For example, for transportation impacts authors would often estimate distances, vehicles, loads, etc. and use generally available data to estimate the resulting environmental impact. The same method was of course used for other fields too.

More agreement appears to exist about the impact that should be used, nearly all the investigated studies used CO2e to express the environmental impact and similar to the previous groups, lifetime energy use was also used numerously.

The subject of the studies was predominantly the comparison of traditional vs. electronic solutions (28), e.g. reading a newspaper vs. reading online news, distribution of a book through a retail store or through the internet, etc. Generally, the studies found that significant reductions in environmental impacts could be achieved when replacing traditional solutions with electronic solutions. However, especially when transport was included, this is extremely dependent on assumptions such as transport distance, vehicles used, number of trips and many more. [81] for example even found that under a certain distance, e-commerce has a higher environmental impact than traditional commerce.

There are several reasons why electronic solutions do not necessarily pose environmentally friendlier solutions. Taking an online shop as an example, in order to order online, there has to be an infrastructure supporting this solution (i.e. the users device, the vendors device, Internet, etc.). When looking at telecommuting, [82] found that naturally energy use at home increases and consequently so does the environmental impact that is caused by that.

It was surprising that, apart from teleconference solutions, only one study did not focus on a comparative view but directly targeted an IT service. [83] conducted a study about how much environmental impact is caused by sending and receiving an e-mail with a 1 MB document. They found that the manufacturing phase causes the majority of potential environmental impacts for the sender's and the receiver's potential whereas for the data center is the use phase. Additionally, the impacts are very heavily influenced by reading time and sender and receiver hold the majority of potential environmental impact.

Looking at the phases that the studies primarily investigated, a clear preference for the use phase is visible. That is due to the strong focus of most studies on comparing two systems (traditional vs. new) and how the change would directly affect the environmental impacts the use of such a system causes.

Table 5: IT-Services Findings

Group	Source	Traditional vs. Electronic	GHG	Air pollutants	Solid waste	Water use	Lifetime energy use	Soil movement	Resources use	Acidification	Eutrophication	Extraction	Production	Use	Distribution	EoL
			Assessed Impact Categories									Life Cycle Scope				
Telecommu-ting	[84]	X	X											X		
	[85][82][87]	X	X	X										X		
	[86]	X	X	X	X	X							X	X		
	[88]	X	X				X							X		
	[89]	X	X				X					X	X	X	X	X
Telecon-ference	[90][91][93]		X											X		
	[92]		X									X	X	X		
Music	[94]	X	X												X	
	[95]	X		X		X			X						X	
	[96]	X	X				X								X	
Print	[81]	X	X	X			X								X	
	[97]	X	X										X	X	X	X
	[98][99]	X					X								X	
	[100]	X					X						X	X		
	[101]	X		X		X			X	X	X	X	X	X	X	
	[102]	X					X						X	X	X	
	[86]	X	X	X	X	X							X	X		
	[103]	X	X				X							X	X	
	[104]	X	X				X			X						
	[105][108]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	[106][107]	X	X											X		
	[109]	X	X										X	X	X	X
	[110]	X	X					X	X				X	X		
Movie	[111]	X	X				X					X	X	X	X	
	[112]	X	X										X	X	X	
Garment	[113]	X	X				X						X		X	
E-mail	[83]		X	X	X	X	X	X	X	X	X		X	X		X

5 Research agenda

Following the framework for literature review [8] it is now necessary to derive a research agenda from the analyzed and synthesized literature. Concluding from the pure amount of found studies for each displayed group there are two different approaches to identify research gaps. On the one hand the researcher can conclude that for the field with the lowest amount of found literature there must be a big research gap. Following this approach our literature review would indicate a research agenda that points towards the group of networks. On the other hand one can argue that a research field producing a high amount of literature is very complex and special aspects are still not yet covered by existing literature. This would indicate a research agenda pointing towards the life cycle assessment of IT-Services. Since production, distribution and consumption of IT-Services partially cover elements of all the other groups (see Figure 1) the research agenda derived from this literature review will focus on this field. Most of the IT-Service studies deal with a very specific situation by illuminating a single IT-Service or by comparing an electronic process with its traditional counterpart. This indicates that there is a need for a more generalized approach for the environmental assessment of IT-Services' lifecycle. In accordance to the formulated aspects and the findings from the literature review, we developed the following potential research questions (PRQ) that address future work on LCA and CF of IT-Services:

- PRQ1. *How can existing concepts of LCA especially methods and approaches of CF be adapted to IT-Services in general?*
- PRQ2. *How can IT-Services be categorized and classified in order to determine environmental impacts?*
- PRQ3. *What model needs to be used or developed in order to display relations and dependencies between IT-Services and IT infrastructure?*
- PRQ4. *Which further aspects besides Carbon Footprint need to be considered for the environmental impact of IT Services?*
- PRQ5. *How is the life cycle assessment useful to IT-Service providers?*

6 Conclusions

Conducting the literature review we found a total of 98 contributions that could be categorized into one of the four groups workplace (36), data centers & server (22), network (7) and IT services (33). There are several important conclusions that can be drawn from the analysis beginning with the not existing clear and fully accepted standards, methodologies or calculation approaches that can be seen as commonly used. Many different approaches were used. Often authors would not even follow known approaches but use customized own methods. The discussions lead to advantages and disadvantages of various approaches and even within these approaches authors are often left with a fair amount of decision freedom regarding structure, scope and methodology. However, the ISO standard and the Eco-Indicator methodology appear to gradually grow into the roles of broadly accepted and used approaches. The assessed environmental impacts also show a wide range, inevitably affected by the lack of agreement just pointed out. There are several aspects that appear to gain momentum over the time, such as the favored expression of environmental impacts in CO_2e and/or lifetime energy use for workplace equipment and exergy energy consumption and/or CO_2e for data centers and server. Similar issues arise for the assumptions that LCAs need to make, a consensus on crucial assumptions (e.g. life span, usage time, power consumption) could not be identified. Additionally, adjacent aspects such as the energy mix used to calculate the environmental impact can have drastic influences on the results and need to be carefully accounted for. All these issues lead to serious concerns from many authors about comparability, consistency and legitimacy of LCAs. Because of the great range in assessed impacts, the wide range of different devices and the issues discussed above, it is difficult to make generalized statements about the results. However, the use phase appears to have the greatest impact for PCs and laptops (roughly 2/3 of CO_2e) as well as data center & server (roughly 90% of CO_2e). Because of the nature of electronic products (numerous, energy intense components) the EoL phase is of particular significance, especially with regard towards effective measures to reduce environmental impacts. As pointed out in the previous chapters, there a various gaps that future research has to fill. In particular, methodologies and standards have to be developed that address the issues made apparent by this literature review. IT service LCAs in general are in need of more research. Despite the comparatively high number of studies found, the focus they show is very one-sided and there are many new aspects regarding IT services that must be investigated especially when keeping current computing trends such as cloud computing in mind. As the realization is growing that ICT is already causing a significant amount of environmental damage and will increasingly do so in the future, so is the realization that manufacturers and researchers need adequate tools to address this issue. Despite the concerns about LCA discussed here, there is a general consensus that LCAs represent a magnificent tool to assess and ultimately help decrease the negative environmental impacts caused by ICT. In order to extend the research agenda from section 5, we derived further PRQs from the conclusions:

- PRQ6. *Which standard(s) should be used to conduct ICT LCA and CF?*
- PRQ7. *How can input assumptions be standardized and which are the driving variables in ICT LCA and CF?*
- PRQ8. *How does the energy mix affect ICT LCA and CF?*

Acknowledgment

This paper arose in the context of the research project “GreenIT Cockpit” funded by the German Federal Ministry of Economics and Technology.

References

Due to space limitations, we provide the complete reference list via an external html link: http://ikmserver.ikm.tu-berlin.de/references/ or as pdf: http://ikmserver.ikm.tu-berlin.de/references/refs.pdf.