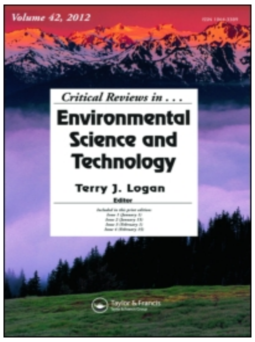

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Review of life cycle assessment on consumer electronic products: Developments and the way ahead

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Review of life cycle assessment on consumer electronic products: Developments and the way ahead

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ABSTRACT

Life cycle assessment (LCA) has grown rapidly and is now well established within the electronics industry. The growing number of journal publications, conferences, and special issues is a proof for the same. A number of literature reviews have been published till now in this area focusing on different aspects. This study has identified 134 significant journal articles to conduct a systematic and narrative literature review. This review covers a wide range of product categories and analyzes the usefulness of LCA as a decision-making tool within the electronics industry which has not been explored fully in previous reviews conducted in this area of research. For this purpose, we organized LCA studies into 10 main product categories. A narrative review was employed to summarize the significant findings from the LCA studies. Although the central objective of all the studies was to evaluate the environmental impact created by the product, the focus and methods employed differed. A systematic review was used to categorize the overall frameworks used in the studies. The studies were classified based on their research purpose, types of approach, LCIA methods used, system boundaries involved, data collection methods, and data analysis levels. Within the subcategory of research purpose, three research domains were identified and the studies were classified accordingly. Generally it has been revealed that use phase, end of life, and production phase are the dominant phases in that order. However discrepancies occur owing to functional units, data usage, and assumptions made. All these and more make benchmarking difficult. Finally we identified gaps that merit attention in future research. It is also hoped that this review is a good resource for anyone interested in doing research on LCA of electronic products, helping them identify current research trends, provide suggestions for future research, and stimulate interest in creating new research directions.

KEYWORDS
Decision-making; electronic products; end of life; life cycle assessment; review; sustainability; use phase

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1. Introduction

Life cycle assessment (LCA) had its origin in the USA during 1960s. Its application to the electronics industry started more than two decades ago with a conference paper entitled "Application of LCA in electronic products" (Rhodes, 1993) in which he described some of the "important applications of LCA pertaining to the interest of the electronics and power products industry. (pg. 101)" Since then LCA has been used as a tool to foster environmentally beneficial electronic products by different researchers in different dimensions over the years. During the last decade, both the electronic products as well as LCA as a decision-making tool (DMT) have grown exponentially. The increasing number of conferences, literature reviews, journal publications, handbooks, and company reports are proofs to these outstanding advancements in these two fields (Taticchi et al., 2014). LCA has matured from a system analysis tool that myopically addressed environmental impacts created by a product or process to a DMT that is capable of analyzing comprehensively the social and economic impacts of a product as well. Simultaneously electronic products have also evolved and gone through tremendous changes both in terms of technological advancements and usage behavior. Growing threats in the form of climate change and health risks have led to the integration of environmental consideration into the design of these electronic products. As stated by the US environmental protection agency "Our 'plugged-in' world relies on an ever-growing and constantly changing supply of electronic products." Going along the global trend, green and sustainable electronic products have received more attention in recent years and harvested new research clusters.

There is a vast amount of literature reviews in the field of LCA of electronic products over the past. Most of the reviews focused on the consumer electronics field in which ICT (Information and communication technologies) products dominate. An overall review has been conducted on ICT product and services (Arushanyan et al., 2014) and some reviews have been carried out in specific aspects such as analyzing inconsistencies, discrepancies, and uncertainties existing across studies linked to ICT devices (Andrae and Andersen, 2010; Teehan and Kandlikar, 2011; Marissa Yao, 2010), comparison of digital and print media (Bull and Kozak, 2014), concept-centric review of IT/IS solutions (Stiel and Teuteberg, 2014), approach of data center industries (Whitehead et al., 2014), and telecommunications industry (Wolfram Scharnhorst, 2006). These reviews have identified and highlighted various issues pertaining to the LCA studies conducted for that specific category of electronic products and their shortcomings. These reviews have uncovered several assumptions made as well as general problems with LCA (Kandlikar, 2011). Both analytical and concept-centric reviews have been conducted and the analysis have been significantly straightforward covering issues like the need to cover usage behavior in a more realistic way, covering informal waste management (Arushanyan et al., 2014), the product life cycle phase that creates more impacts (Bull and Kozak, 2014; Teehan and Kandlikar, 2011), need for further methodological developments in the field of LCA (Wolfram Scharnhorst, 2006), environmentally sound management of End-of-Phase (EOL) phases of mobile phones and the emphasis on the inconsistencies between different LCA studies conducted for desktop PCs, notebooks, mobile phones, and televisions (TVs), and how these discrepancies in results sometimes make benchmarking difficult (Andrae and Andersen, 2010).

2. Research motivation

All the reviews mentioned in the previous section and many more have provided in-depth analysis and useful insights in this field. However, these studies have reviewed only fractions of the large electronics industry that have used Environmental Life Cycle Assessment (ELCA) as a tool to identify and analyze the environmental impacts. By far, reviews comprehensively covering all the electronic product categories are hardly found in the literature. To the best of our knowledge, no comprehensive review of application of ELCA in a varied range of electronic products has been published so far. The focus so far has been mainly on ICT products and services. A holistic review that has categorized and prioritized a range of products in electronics sector for conducting ELCA is clearly missing in the published literature. To comprehend the above mentioned shortcomings, in this work we set out to conduct a diachronic and holistic literature review covering ELCA studies on a wide range of electronic products from 1995 to 2015. For this, we conducted a narrative literature review of peer-reviewed publications on the topic "ELCA and electronic products" from a theoretical point of view and hope that this analysis of the literature will provide useful insights for the readers and researchers on LCA studies of specific electronic product categories.

LCA is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, that is, from raw material acquisition, via production and usage phases to waste management (ISO, 2006a). LCA as a system analysis tool has undergone strong development and harmonization has occurred resulting in international standards. Over the years, the maturity and methodological robustness of LCA has increased evidently (Hans de Bruijn, 2002).The concept of ELCA is well established in the electronics industry. However still it cannot be holistically utilized as a DMT owing to a number of reasons, one which is the lack of consistency within the available studies. The inconsistency is primarily due to the assumptions made in terms of the life span of the product, different system boundaries involved, selection of indicators, and reporting of results. Even for the same product these inconsistencies prevail, making it difficult to compare results and establish trends within the electronics industry. Though some frameworks, methods, and models were developed by authors in the last two decades, still holistic approaches using LCA as a DMT in the electronic industry have definitely space to improve. In this context, another objective of this research work is to assess the developments made so far in using LCA as DMT in the electronics industry, aiming to identify knowledge gaps and derive future research agenda. Also the primary limitation of previous reviews conducted in LCA of electronic products is the identification of research domains. So the authors of this work tried to narrow this gap by identifying research domains in this field, which will help determine the potential of LCA as a DMT in the electronics industry. For this, we have performed systematic literature review of the published work in this research area (Taticchi et al., 2014). Therefore, this review has the following specific objectives:

Narrative Literature Review objectives:

1. To capture the existing ELCA studies on a wide range of electronic products and classify those into a number of relevant product categories.
2. To examine the published literature under each category and present the LCA results of individual studies under each product category.

Systematic Literature Review objectives:

3. To describe the nature of ELCA-related articles on electronic products using various descriptive statistics.
4. To identify and classify implementation of ELCA in electronic products into various research domains.
5. To conclude research trend, identify knowledge gaps, and provide future research recommendations from the perspective of using LCA as a holistic DMT in the electronics industry.

3. Narrative literature review

The overall aim of this narrative review is to analyze and present the spread across publications within the studied body of literature. For this, the conventional way of summarizing the relevant studies within a wide range of electronic product categories is carried out and the reported results are presented in this section.

Few studies focused entirely on assessing the product using LCA as a tool while others addressed the aspect of methodological developments in LCA of electronic products and used computers, mobile phones, and other products as case studies to test their findings. Few aspects that these bulk of LCA studies have in common, new developments made through a few of these studies, and major conclusions agreed upon by most of the studies are collated and presented in Table 1 under different product categories. Within each product category, individual studies are compared based on their major focus/contribution and conclusions/findings, and presented in Tables 2–11 with author citations.

3.1. ICT devices

Computers including desktops & notebooks, mobile phones, computer displays, electronic media, and television were the assessed products in this category by many researchers in various dimensions.

Table 1. Major commonalities and conclusions collated from the LCA studies.

Product categories	Commonalities among studies	New development/findings	Majorly agreed/concluded results
Desktop and laptop computers	Used conventional LCA technique to assess environmental impacts/ carbon footprint; usage of secondary data; LCA is used for comparative purposes and regional analysis mostly	Introduction of new concepts like spatial environmental balance (SEB) and global change mix factors (GCMF); development of methods like advanced attributional LCA (AALCA); consideration of factory through mall phase in LCA	Production phase followed by use phase is the dominant phase in creating impacts; use phase is impacted due to operational energy; E-commerce when used creates lesser impacts
Computer displays	LCA technique used to compare liquid crystal display (LCD) and cathode ray tube (CRT) display of computer monitors mostly	Normalization and weighing using Korean values; CRT can be used as a secondary raw material in ceramic glazes and reduce impacts	LCD monitor disposal has lower impacts compared to CRT; carbon emissions reduce when recycled materials are used; extended life span of the product reduces energy and eco-impacts
Mobile phones	LCA as a technique to assess and compare mobile phones; compare UMTS and GSM mobile communication systems; compare 2G and 3G networks	Mobiles phones at EOL can be repurposed as car parking meter with battery; direct land use (DLU) was assessed and concluded to create impacts	Production phase followed by use phase is the dominant phase in creating impacts; recycling of materials is beneficial; UMTS was better; short life span of the mobile phones increases the impacts; recycling of network materials is very beneficial
Electronic media	Most of the published work was related to comparing electronic media (tablets, internet) with traditional and conventional methods like paper and printing (magazines, newspapers) with the aid of LCA.	LCA to compare the energy consumption related to digital and traditional library concentration on journal collections	Production phase was concluded to create more impacts; paper and pulp production influenced impacts in the print; no conclusions were derived between e-media and print media; though in cliche e-media seems better it involves lot of uncertainties in allocation, inventory concluded most of studies
Television	LCA technique used to assess the environmental impacts of different TV sets and compare the displays used in TVs	LCA of plasma TV and comparison of LCD and CRT display used in it for the first time; fire LCA was performed on TV sets	Production and use phase were reported to be the clearly dominant phases creating impacts; mechanical recycling shows negative impacts; mercury in LCD and copper in plasma TV induces negative impacts
E-waste	Gate-to-grave analysis is done and LCA is carried predominantly for the EOL processes	Development of material index and web based decision support system for effective management of recycling, electronic product disassembly and materials recovery	More mechanical recycling and less incineration was emphasized; smelting process in EOL created more impacts; usage of recycled materials reduced greenhouse gas (GHG) emissions; human health is the affected impact category

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Table 1. (Continued)

Product categories	Commonalities among studies	New development/findings	Majorly agreed/concluded results
Intermediate products / processes	LCA used as a technique to assess the environmental profile of intermediate products like solder, PCBs, batteries mostly; LCA also used for product comparison in some studies	LCA for comparing Eco mouse proto type with original and paper PCB prototype with the original was an innovative approach; lead free solders are a new development but increased global warming potential (GWP)	Raw material extraction is the most dominant phase with copper production inducing more negative impacts followed by silver and tin; Li batteries are main source of metal pollutants; rechargeable batteries definitely are eco-friendly option compared to primary batteries; GWP and Ozone layer depletion (ODP) are the most impacted categories
White goods	LCA studies related to large household appliances including air conditioners, refrigerators, and washing machines for assessing the environmental profiles of individual products and for comparative purposes	Reverse LCA performed to design ideal green product; demonstration of inverse WM effect to avoiding double counting of use phase is a new development	Usage and production are the dominant phases; replacing HCFC22 with HFC410A in ACs reduced impacts; centralized systems are reported to create lesser impacts compared to individual systems; magnetic refrigerators and hermetic compressors create more impacts;
Domestic appliances	Environmental impacts created cumulatively by a bunch of household appliances in a large scale are analyzed using LCA	New approach to handle relatively huge data sets in LCA was proposed; consumption based LCA to model consumer electronic products (CEPs) for a 15-year period	Use phase was reported the most dominant phase; fossil fuel depletion, respiratory inorganic, acidification, eutrophication, and radiation were reported as the most relevant impact categories
Low-profile electronic products	Small and personal electronic products without much complex intermediate products or processes are analyzed using LCA	LCA of such small products like toys, remote sensor itself a very important contribution as these kind of products are most likely ignored and considered not to create much impacts	Each study has identified different phases as dominate, as the products vary, so no major conclusion could be derived

3.1.1. *Desktop PCs and laptops under the umbrella of ICT devices*

Table 2. Comparison of desktop- and laptop-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the study	Major findings/conclusions
Desktop computers		
Norris et al. (2003)	Retailing and wholesaling were for the first time considered in LCA modeling; factory through mall phase was tested for the first time	Production followed by factory through mall were the phases that created most impacts; E-commerce can make huge difference in energy efficiency
Junnila (2008)	IO LCA of energy-consuming products was carried out at company level in Finland	User phase was found to dominate in creating impacts due to the operational energy

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Table 2. (Continued)

Author	Major contribution/focus of the study	Major findings/conclusions
Teehan and Kandlikar (2013)	Compared 11 ICT devices by assessing the environmental impacts created by them, a decade ago and now, using Process-Sum LCA; a new primary data set for the inventory and linear regression-based models were explored in LCA	GHG emissions reduced by 50–60% in new age products mainly due to the proportional decrease in ICs and PCBs in ICT products
Maga, Hiebel, and Knermann (2012)	LCA on desktop PC and thin client computing (server-based computing in combination with thin clients (SBCTC)) system in a work place in Germany	Use phase was concluded to be the most impact-creating phase due to electricity consumption
Andrae (2014)	Newly developed method called advanced attributional LCA (AALCA) was performed on office computing systems and smart phones to assess the GWP; new concept of global change mix factors (GCMF) was used for the first time	AALCA method proved to be better than the existing ALCA method
Malmodin et al. (2010)	LCA on ICT to assess the operational electricity usage and carbon footprint relating to ICT in Sweden	Shared data transport networks & data centers and manufacturing of network infrastructure were assessed for the first time
Daiyue et al. (2015)	Introduced the concept of spatial–environmental balance to describe a region's environmental balance based on LCA studies of various products in that region	Consideration of geographical factors into the environmental assessment of different ICT product categories
Mirabella et al. (2013)	LCA of ICT product to evaluate two scenarios in a public administration office in Italy	Traditional system creates more impacts and transportation is the dominant phase
Hishier (2015)	LCA on ICT devices and compared the results in three perspectives including individual, family, and global sales; for the first time have evaluated overall energy termed as gray energy of an ICT product	Resulting impacts are mainly affected by the assumptions made in the usage phase; emphasize the relevance of production phase in terms of energy consumption
Qingbin Song et al. (2012)	Compared the LCA results of LCD and CRT screens of the PCs in Macau	Manufacturing and use phase clearly dominate the impacts
Duan et al. (2009)	LCA on a Chinese desktop PCs	Manufacturing and use phase are the dominant phases
Choi et al. (2004)	Effectiveness of recycling waste PCs in Korea was evaluated using LCA	Emphasized that premanufacturing is dominant in creating impacts; ozone depletion potential and eco-toxicity has not been effectively reduced in the disposal stage
Gay et al. (2005)	Company-level analysis of selling Dell PCs; compared the traditional and E-commerce way of selling PCs	Distribution followed by packaging creates impacts; e-commerce was concluded to create lesser impacts
Hossain et al. (2014)	Developed a conceptual framework called Auto LCA and performed LCA on four product categories including desktop computers	Proved to be a simplified method providing similar results when compared with labor-intensive current LCA methods
Masafumi Tekawa (1997)	Product comparison between laptop PC and desktop PC	Use and production stages need more attention
Laptop computers		
Deng et al. (2011)	Economic balance hybrid-LCA with uncertainty analysis was used to model the life cycle impacts of a laptop computer	Manufacturing phase needs more attention over operational phase in terms of energy use and carbon emissions
Streicher-Porte et al. (2009)	Regional-level analysis was performed in Columbia in which three computer supply scenarios (local refurbishment, overseas donations, purchase of low-cost computers form Korea) to schools in Columbia was evaluated	local refurbishment of second hand computers was the most sustainable solution

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Table 2. (Continued)

Author	Major contribution/focus of the study	Major findings/conclusions
Lu et al. (2006)	Regional-level analysis was carried out in Taiwan to evaluate the environmental impacts of recycling notebook computers	Recycling of some components actually results in greater negative environmental impacts
Satoshi Oikawa (2005)	LCA on two notebook computers that were manufactured 8 years apart	Service value, core hardware specifications, CPU clock size were compared for GWP
Stutz and O'Connell (2010)	Carbon footprint assessment of a DELL laptop was carried out	Manufacturing phase needs more attention

3.1.2. Computer displays under the umbrella of ICT devices

Table 3. Comparison of computer display-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Andreola (2005)	LCA on a computer and TV with CRT monitor; resource depletion is the most relevant impact category	Recovered CRT can be used as a secondary raw material in ceramic glazes and reduces in environmental impact
Fernanda Andreola et al. (2006)	LCA study on recycling of EOL CRT glasses into ceramic glazes	Environmental impacts especially carbon emissions considerably reduced when such recycled materials are used instead of virgin materials
Williams (2004)	LCA on a desktop with 17″ CRT monitor using hybrid-LCA methodology	Extending the usable life span of the product by reselling or upgrading will only mitigate the energy and environmental impacts created by the product in its manufacturing and disposal stage
Seungdo Kim (2001)	Assessed the environmental performance of a color computer monitor made in Korea; normalization and weighing was done for Korean values; LCI data were also collected for the foreground processes	Categorized the hot spots into controllable (that can be improved by the company and suppliers) and uncontrollable (like raw material extraction processes and usage behavior of consumers)
Maria Leet Socolof (1999)	Life cycle design tool to manage complex LCI data and handle impact calculations was developed and used to assess the impacts of CRT and LCD monitors	Chemical toxicity impact was given more significance
Socolof et al. (2005)	LCA on CRT and LCD desktop computer displays	Energy usage in the production phase of CRT glass creates most impacts
Noon et al. (2011)	Only the EOL phase of the computer monitors in the Seattle region of the US was analyzed using LCA; expected regional change in monitor disposals between the year 2008 and 2010 were studied	LCD monitor disposal had lower impacts compared to CRT; two scenarios—one in which credit was given for avoidance of primary material production and the other in which no credit was given for the same criteria; scenario one produced lesser impacts
Zhou and Schoenung (2007)	Cradle-to-gate LCA was performed on computer display	Integrated Industrial Ecology Function Deployment (I2-EFD) was developed to make material selection more feasible

3.1.3. Mobile phones under the umbrella of ICTs

Table 4. Comparison of mobile phone-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Zink et al. (2014)	Three types of reuse options (traditional refurbishment, repurposing as car parking meter with battery and repurposing with solar power) for mobile phones were studied and compared	Repurposing as car parking meter with battery was concluded as the most environmentally friendly reuse option
Yu et al. (2010)	LCA was used to analyze the manufacturing, usage and disposal phases of mobile phones produced in China	Manufacturing phase was concluded to consume more energy and create negative impacts
Park et al. (2005)	New conceptual method was developed to assess the environmental impacts based on Delphi method and compared with LCA technique	Raw material extraction was concluded to be the most negatively influential life cycle phase; developed method though not as accurate as LCA is still better
Sibylle D. Frey (2006)	To analyze the ecological footprint of three mobile phones	Direct land use (DLU) has been assessed and concluded to be the category that creates significant environmental impacts
Faist Emmenegger et al. (2004)	For the first time, LCA of UMTS (mobile communication system) was done in Switzerland and the results were compared with the previous system GSM	UMTS was better at that point and time; short life span of the mobile phones increases the impacts created in the production phase, electricity mix influences the negative impacts, and the base station contributes to impacts due to usage behavior
Anders S. G. Andre (2000)	A comparison between the environmental impacts created by an old (BC 8) and a new model (BC 10) of a private branch exchange (PBX) system, namely, the MD 110 system was carried	Energy use in the use stage due to combustion of fossil fuels & hardware (ICs and PWBs) manufacturing stage were confirmed as the most impact creating life cycle phases
Taiariol et al. (1999)	LCA was carried on the EOL phase of telephone exchange equipment; primary data were used from the site	Material components like copper, palladium, aluminum created more impacts
Moberg et al. (2014)	A comparison between five different simplification approaches was carried out	Input-output data were confirmed to be the most feasible simplification method especially when specific data are lacking
Scharnhorst et al. (2006)	LCA was conducted on 2G and 3G mobile phone networks; GSM and UMTS networks were compared with emphasis on EOL phase	Number of subscribers and total download volume were considered to be the most influencing parameters; recycling of electronic scrap showed environmental benefits and material recycling proved to lower the environmental impacts in the production phase by half
Wolfram Scharnhorst et al. (2005)	LCA on a 2G mobile phone with GSM network primarily focusing on EOL phase	Use phase is dominant; production phase also generates reasonable impacts due to the manufacture of PWBs and EOL phase creates more impacts on the eco-system quality, heavy metals contribute to negative impacts in the EOL stage and it is also concluded that recycling of network materials is very beneficial also rare metals recovered result in reduced impacts on human health
Hibbert and Ogunseitan (2014)	An experimental analysis of a set of cell phones was done; dismantled into 4 parts namely batteries, circuit boards, plastics and screens; emphasized on the wrong implication of burning discarded mobile phones to recover rare metals by artisanal mining in the EOL phase	Copper in the PCB had the eco-toxicity impact; incernation was confirmed to contribute the most negative environmental and human health impacts in the EOL management

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Table 4. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Moraes et al. (2014)	A regional-level LCA analysis was done to assess the environmental implications of two reverse logistics scenario of cell phones in Brazil; two scenarios were compared	Second scenario is more beneficial in terms of reduction of acidification; photochemical oxidation, eutrophication and the use of nonrenewable energy; emphasized that such arrangement in Brazil would certainly provide job opportunities and increase socioeconomic income
Yang et al. (2004)	An LCA on mobile phone housing was performed in China using primary data from the company MOTOROLA; emphasized on material flow analysis to be used in selection of environmentally friendly processes	Photochemical ozone formation is the most relevant impact category and housing decoration processes is the most impact creating phase; electroplating technique proved to be more environmentally beneficial when compared to VDM owing to the energy and raw material used

3.1.4. Electronic media under the umbrella of ICTs

Table 5. Comparison of electronic media-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Vlad C. Coroama (2014)	Comparison between electronic media and newspapers; only GHG emission was assessed	Production and consumption were determined as dominant phases; electronic media may not be a thoroughly beneficial option unless its potential is sought out
Achachlouei and Moberg (2015)	Compared the case of print and tablet version of reading a magazine using LCA	Use phase with eutrophication and metal depletion as the most relevant impact category
Moberg et al. (2010)	A screening LCA to compare the environmental impacts created by printed and tablet newspaper	Production phase with ozone depletion as the most relevant impact category
Scott Matthewsa and Hendricksond (2002)	Compared traditional and online retailing of books in the US and Japan using two types of LCA (EIO LCA and conventional LCA); not much of difference between the two types of LCA employed; e-commerce was found to be more beneficial when no air freight is added and courier service is used in times where consumer had to commute to the store to collect books using a personal vehicle	Energy consumption was concluded as the most relevant impact, air freight transportation in the case of the US; packaging, population density and number of books per order in Japanese case were the life cycle phases that generated most impacts
Reichart and Hischier (2002)	Evaluated and compared the environmental impact of getting a news through TV broadcast, newspaper, and internet using LCA	Printed newspapers showed more negative impacts when compared with online news and TV broadcast owing to more impacts in the manufacturing stage of pulp and paper
Tagami and Williams, (2003)	Compared an online and conventional retail book sector in Japan using LCA	Transportation in urban areas created more impacts; energy efficiency in distribution phase can be improved by reducing impacts caused by packaging, loading trucks, number of trips per delivery, and residential energy consumption
Malmodin et al. (2010)	Carried out a sector-level comparison between ICT and the entertainment & media sector	Considering the manufacture and operation phase E & M sector projected more GHG emissions by 2007 when compared to PCs

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Table 5. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Schien et al. (2013)	Analyzed the usage phase of the online multimedia services using LCA	Energy use by devices and 3 G network influence the service footprint
Gard and Keoleian (2003)	Used LCA to compare the energy consumption related to digital and traditional library concentration on journal collections	Energy consumption is highly influenced by number of readers per article, personal transportation tends to dominate, laser printing was found to be beneficial when compared to online reading, networking had less effects, and photocopying always increased the impacts of energy consumption
Borggren et al. (2011)	A comparison between a book purchased online and from a book shop was analyzed using LCA	Apart from the paper and pulp production phase which creates more impacts, other attributes like e-commerce involved in distributing these books; personal transportation in buying these books from store significantly influences the impacts of traditional retailing
Finnveden (2011)	A comparison between e-book reader and a conventional book was done	Not able conclude as to which one is better as the lifetime of the device, disposal of the device, and EOL management options had a lot of uncertainties and there was lack of data as well
Hischier et al. (2014)	Compared electronic media and print media; two types of LCA were carried out; one using desktop based LCI data and the other using lab-based LCI data after dismantling	How the LCA results vary significantly for the same product category was highlighted; the main attribute as determined by the authors is the inventory used to conduct LCA in both scenarios
Moberg et al. (2010)	Screening consequential LCA on electronic voicing in the year 2010 in Sweden	E-invoicing cannot claim to be completely environmentally beneficial over traditional method, though seems like in cley she, as it involved attributes like allocation, printing not included in e-voices and how the e-voice system was designed

3.1.5. Television under the umbrella of ICT devices

Table 6. Comparison of television-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Huulgaard et al. (2013)	Performed a consequential LCA on TV; GWP and RIP were the two impact categories that were assessed	Other hot spots apart from energy consumption in the use phase has to be addressed in eco-design; production was the most attention-seeking life cycle phase
Feng and Ma (2009)	Energy consumption and environmental impacts of 10,000 color TVs produced in China were evaluated using LCA	Manufacturing and production stage were the most problem creating ones and air emissions from the fossil fuel utilization was the most relevant impact category
Lim and Schoenung (2010)	Evaluated the flat panel displays of four product categories including LCD TV, and plasma TV; pathway and impact assessment model for heavy metal content was developed	LCD displays were concluded to create less environmental impacts when compared to CRT display except for the ecological toxicity category; new devices show negative impacts in this category because of the mercury in the LCD TVs and copper in the plasma TV

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Table 6. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Hischier and Baudin (2010)	Detailed LCA study on plasma TV was conducted for the first time; first time comparison of LCD and CRT technologies used in PDP TV was also done	Production and use phase clearly dominate as high impact phases; distribution phase was irrelevant and EOL phase was beneficial
Thomas et al. (2011)	LCA on a 40-in LCD flat screen TV, assessing the single impact category of GWP	Emissions from the use stage was modeled in this study and the significant source of NF3 emissions was analyzed in this work
Song et al. (2012)	Carried out LCA of the CRT monitors used in TVs produced in China	Use phase clearly dominate due to electricity consumption followed by manufacturing of CRT and PCB components; incernation influenced the negative impacts in the EOL phase. Acidification and eutrophication were concluded as the most relevant impact categories in the use phase
Rocchetti and Beolchini (2014)	the EOL of CRT used in TVs was modeled using LCA; fluorescent powder treatment process was assessed; yittrium recovered using this process created less impacts in terms of Co2 emissions when compared to the original production of yittrium metal	GWP was determined as the most relevant impact category and material recovery phase was found to influence the negative impacts in the EOL phase
Hischier (2014)	Conducted LCA study on field emission display TV with three types of display technologies currently available (LCD, CRT, plasma)	Metal depletion and ODP were the most relevant impact categories, and production phase was determined to be one that needs more attention; the FED TV showed environmental advantages
Hochschorner et al. (2015)	Region-based study on carbon footprint of a movie viewed via internet in alternative scenarios was evaluated and compared in Sweden using LCA	Manufacturing and use stage due to electricity consumption followed by the distribution phase due to construction of cables were the most negative impact creating phases; P2P showed higher impacts compared to the IPTV systems of watching movies
Dodbiba et al. (2008)	Different treatment option of the plastics from old TV sets in its EOL phase was evaluated using LCA	Mechanical recycling created most negative impacts compared to energy recovery option
Margaret Simonson (2002)	A fire LCA was performed on TV sets with V0 and HB material in Sweden; first if its kind to compare TVs with and without flame retardant plastics	Emissions from the entire life cycle of nonflame retardant TV was higher compared to flame retardant TV during the time this study was conducted.

3.2. E-Waste

Table 7. Comparison of e-waste-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Wager et al. (2011)	Conducted LCA on the Swiss WEEE collection and recovery system which included collection, preprocessing, and end-processing as well as of incineration and landfilling; compared environmental impacts WEEE scenario from 2004 to 2009 in Switzerland	More recycling and less incernation was recommended by the authors in treatment of plastics and adequate environmentally friendly modeling for treatment of metals, cables or CRT devices was also emphasized

(*Continued on next page*)

Table 7. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Herrmann et al. (2004)	Developed a material index	The metals recovered by material recycling in the EOL phase of electronic products were assessed
Menikpura et al. (2014)	GHG emission mitigation was specifically targeted and assessed based on an excel calculation sheet using LCA in Japan	Smelting process in the EOL processes as the dominant one in creating impacts
Gamberini et al. (2010)	Transportation involved in WEEE operations was assessed using LCA; saturation of vehicle capacity and the utilization of vehicle working times were evaluated; collection process in relation to transportation has been analyzed for the region of Italy	A comparison between GHG elision from virgin materials and recycled materials was carried out; recycled materials clearly reflected reduced GHG emissions; different solution were compared to derive the best one
Biganzoli et al. (2015)	Region-based assessment was carried out in Italy in the Lombordia region, where the existing WEEE management system was evaluated; primary data were used	ODP and human toxicity were the most relevant impact categories; overall LCA results proved to be environmentally friendly; recovery of metals, plastic, and glass gave benefits
Alston and Arnold (2011)	The environmental impacts associated with pyrolysis; an EOL treatment option for plastics was carried using LCA; compared with other options like material recycling and incernation	Not able conclude as one of these methods as "best"; however pyrolysis had the advantage due to the oils and gases released which can be used as fuels and save resources without high impact on land space and climate change
Bigum et al. (2012)	Recovery of metals like aluminum, copper, gold, iron, nickel, palladium, and silver from high-grade WEEE using LCA modeling	Operations involving pretreatment created less impacts compared to metallurgy treatment and also emphasized that metals recovered in these EOL processes must be quantified individually and not in bulk for better results
Zhang et al. (2004)	Developed a web-based decision support system	Effective management of recycling, electronic product disassembly, and materials recovery was presented
Rubin et al. (2014)	Two material recovery processes used in EOL treatment of WEEE to treat PCB scrap were evaluated and compared using LCA	the process of aqua regia is environmentally beneficial and AEP is the most relevant impact
Niu et al. (2012)	LCA was used to assess the treatment options used to handle CRT display scrap in WEEE management	Human health is the most affected category and incernation process is the most impact creating operation
Dodbiba (2007)	Energy recovery and mechanical recycling; two main EOL processes are compared using LCA, and recovery is restricted to recycling of plastics form discarded TV sets in Japan	Mechanical recycling is a wiser option when compared to incernation for energy recovery and reduction of PVC will considerably reduce environmental impacts in the recovery process; GHG emissions was the most relevant impact category

3.3. Intermediate products/processes

Table 8. Comparison of intermediate product/process-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Vasan et al. (2014)	Commercial- and military-grade DC–DC buck converters were evaluated using hybrid LCA and CF was calculated	Raw material stage created most impacts

(*Continued on next page*)

Table 8. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Dahlben et al. (2013)	Semiconductor device used in cell phones was assessed using LCA	Gold refining processes and electricity generation were concluded as the dominant phase
Kang et al. (2013)	Rechargeable lithium batteries in electronic waste of cell phones were evaluated using LCA; three battery types were also compared	Li batteries are sources of metal pollutants like Co, Cu, Ni, and Pb when disposed by landfill; Human health, resource depletion, and eco-toxicity were the most relevant impact categories
Mayers et al. (2005)	Printer recycling in the UK was carried out using LCA; four management options and nine impact categories were assessed	Not able to arrive at a conclusion as to which one is best as the results depend on the kind of material recovered and the type of process used for it
Andræ et al. (2005)	ICs and PCBs used in digital phones were modeled and assessed using LCA for GHG emissions; a LCI data collection model was developed	Emphasized the significance of evaluating intermediate products and processes in the life cycle of electronic products
Lee and Park (2001)	PCB-component of a hard disk drive was assessed using LCA; understandable and meaningful representation of LCA results was developed in this work which met the type 3 declaration	Production of copper-clad laminate proved to be the most impact creating process
Andrae et al. (2004)	SIP switch product was evaluated using LCA and hot spots were identified in the manufacturing stage	Electricity consumption in spin coating process; spin coating in manufacturing process and copper consumption in deposition process were determined as the dominant phases; GWP and ADP were reported as the most relevant impact categories
Lankey and McMichael, (2000)	Primary and rechargeable batteries were compared using hybrid LCA	Rechargeable batteries are better when compared to primary batteries; GWP and ODP were the most relevant impact categories
Pascal De Langhe (1998)	ADSL high-speed modem-telecom products were assessed using LCA; a comparison between the original and the newly developed model with green design was done	Newly developed one proved to be better, use phase was the most dominant phase and acidification was the most relevant impact category
Weber (2012)	Server was assessed using LCA; major uncertainties and variability in PCF accounting such as in use profile characteristics, logistics calculations, and electricity mix uncertainty were quantified	Emphasize on concentrating more on the energy efficiency in the use phase
Andrae et al. (2007)	Notion that "a typical lead free solder paste Sn95.5Ag3.8Cu0.7 is worse than Sn63Pb37" was tested using consequential LCA and LIME weighing method for the first time	Resource consumption was the dominate phase, and silver and tin production phases also need attention
Sarah Boyd (2011)	EIO-LCA of NAND Flash Memory was carried out	GWP was the most relevant impact category and production and use phase were the dominant ones
Parsons (2006)	Environmental impact of disposable and rechargeable batteries used in consumer electronic products were assessed in Australia using LCA	Rechargeable batteries clearly show environmental benefits
Liu et al. (2014)	Paper-based printed circuit boards which are the future was assessed using LCA; authors created a P-PCB prototype and compared it with O-PCB	P-PCB is 2 times environmentally beneficial than O-PCB, especially when a regional or global production level is considered
Elduque et al. (2014)	Domestic induction hob fixed on electronic boards was assessed using LCA	ODP was the most relevant impact category and is caused by Touch Control PCBA, ELIN PCBA also influences negative impacts, and EOL treatment was the dominant phase

(*Continued on next page*)

Table 8. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Andrae and Andersen (2011)	Integrated circuit packaging technologies, the sub structures of electronic products was evaluated using screening LCA, ball grid array (BGA) and chip scale packaging (CSP) are evaluated for the first time; a comparison between BGA packages using different types of metal-plated monodispersed polymer particle (MPP) balls and conventional balls is also carried out	The authors conclude stating that environmental performance of BGA/ CSP can be improved by concentrating on ball production, again in this study only GHG emissions were studied
Ekvall and Andrae (2005)	Lead-free solders were assessed using attributional and consequential LCA, Sn–Pb solder and a Pb-free were compared, and the two LCAs were also compared	The authors conclude that this shift to lead-free solders has led to reduced emissions but increased GWP, regarding the two LCAs used the authors conclude that consequential LCA still needs more readily available marginal data and input data for modeling
Iakovou et al. (2009)	Framework was developed for effective EOL management of electronic products and ISDN network terminal was assessed as a case study	Multicriteria matrix was used by the authors to rank the material components based on their environmental and economic benefits, which would help manufacturers take decisions
Eun et al. (2009)	Environment information system including PDP, liquid crystal display, cathode ray tube, and rechargeable batteries which are linked to online LCA tool were used to develop a hybrid LCI inventory; authors also compared hybrid LCA with conventional LCA	Concluded that hybrid LCA is more effective in particular for electronic industry which imports raw materials in large scale
Schneider et al. (2008)	Prototype of an eco-mouse with ideal ecological characteristics was developed by the authors in this work and streamline LCA was used to evaluate and compare the original mouse and the developed proto type	Eco-mouse proved to environmentally beneficial; however, use phase was reported to be the dominant phase by the authors

3.4. White goods

Table 9. Comparison of white goods-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Air conditioners		
Shah et al. (2008)	Residential heating and cooling systems were evaluated and compared using LCA between four regions in the US	AC was concluded to create high impact in all damage categories
Yokota et al. (2003)	GWP of ACs in Japan was studied by integrating LCA and population balance model (PBM)	Total GWP created between 1990 and 2010 was calculated; shorter life span of ACs will reduce the GWP if recovery percent is 50%
Yanagitani and Kawahara (2000)	Two ACs (HCFC22 being used for its refrigerant and the other is with HFC410A) in residential use were compared	Replacing HCFC22 proved to reduce the overall environmental impacts; EOL management was reported as the dominant phase and GWP the most relevant category

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Table 9. (Continued)

Author	Major contribution/focus of the work	Major findings/conclusions
Techato et al. (2009)	Waste treatment of used ACs was evaluated using LCA in Bangkok waste treatment facility	These are small amounts, but when calculated on a global level results in huge damage
Grignon-Massé et al. (2011)	A regional-level analyses in Europe, where five different scenarios of ACs were assessed using LCA	GWP and energy consumption was assessed and usage phase was reported as the dominant phase
Gheewala and Nielsen (2003)	Centralized and individual AC systems were evaluated and compared using LCA in Thailand	With respect to environmental impact and resource consumption, centralized system was reported as more environmentally beneficial
Refrigerators		
Xiao et al. (2015)	LCA was performed for a direct-cooling double-door household refrigerator in China; hot spots were identified as usage phase and resource consumption including and natural gas in the assembly phase	Among the multiple categories assessed, 11 are high in usage phase and 4 (ODP, TETP, ADP-elements, and ADP-fossil) are high in production phase
Monfared et al. (2014)	LCA was performed on a magnetic household refrigerator with permanent magnets and a conventional vapor compression refrigerator	Climate change and water depletion are reported as the most relevant impact categories; production and use are the dominant phases; use phase due to electricity mix involved shows high impacts; magnetic refrigerator shows more impacts due to the presence of rare metals used
Tasaki et al. (2013)	Hypothesis that replacing old gadgets with new energy-efficient equipment reduced impacts is tested using TVs, refrigerators, and ACs	The authors have made an attempt to develop an assessment approach where the customer can understand the environmental implication of changing these products and take a decision; the authors also report pertaining to the case studies that only replacing TVs created more impacts
Christopher Ciantar (2000)	Manufacture and recovery of refrigerants was evaluated using LCA	GWP was reported as the most relevant impact category; hermetic compressor were reported to contribute to most impact categories
Washing machines		
Park et al. (2006)	EOL phase of washing machines (WM) was evaluated, comparison of four methods was done, and economic variant was also integrated with environmental quotient	Recycling and eco-design were overall emphasized by the authors to reduce impacts; steel frame contributed to more impacts in three methods and in eco-efficiency method; transformer influenced impact mostly; PCB was component of major concern in all the four methods in EOL
Graedel (1997)	Reverse LCA was performed on the current washing machines in order to design an "ideal green product"	After reviewing possibilities, suggestions for clean clothing is provided by the authors
Ardente and Mathieux (2014)	LCA is used to compare two energy-using products under two scenarios one with normal lifetime and the other with extended lifetime; a general and specified index is developed	When lifetime is extended, the impacts were reported to reduce but with certain limitations like the type of impact category selected, amount of repair, and the efficiency of the replaced product
Cullen and Allwood (2009)	LCA is carried on clothing, WM and detergents individually, and cumulatively LCA of WM is done; the reason being to demonstrate "inverse WM effect"	Double counting of the use phase impact occurs, and the authors also state that transportation plays a significant role in contributing to impacts

3.5. Domestic appliances

Table 10. Comparison of domestic appliances-related LCA studies based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Ryen et al. (2015)	Consumption-based LCA was used to model and assess the CEPs owned by an average US household for a period of 15 years	CED and GHG emissions were the two impacts categories studied; use phase was reported as dominant phase
Gutiérrez et al. (2009)	New approach to handle relatively huge data sets in LCA was proposed; the domestic appliances were categorized into four categories; data sets were handled using the developed approach and LCA was carried out on EOL phase of the domestic appliances	Principal component analysis and multidimensional scaling were reported to efficient in handling huge data sets; fossil fuel depletion was reported as the most relevant impact category
Gutiérrez et al. (2010)	Nine domestic appliances were evaluated and compared by integrating MDS (multidimensional scaling) technique in the interpretation stage of LCA	WM and fridge were reported to create most impacts, again only EOL phase was considered, minerals impact category, acidification, respiratory organics, and eco-toxicity were the most relevant categories
Barba-Gutiérrez et al. (2008)	Data envelope analysis (DEA) was carried out based on LCA to calculate, compare, and position a bunch of domestic appliances based on the environmental impacts created by them	Cell phones were reported to be the most environmentally beneficial; fridge, computer, and WM contribute to negative impacts in that order
Barba-Gutiérrez et al. (2008)	LCA was applied to EOL phase of a group of domestic appliances to find out the threshold beyond which collection of WEEE is harmful and the environmental implication due to the WEEE regulations in Europe was also highlighted	Fossils fuels, respiratory inorganic (winter smog), acidification, eutrophication, and radiation were reported as the most relevant impact categories; transportation of WEEE to EOL processes was reported to create maximum impacts
Nakano et al. (2006)	GWP caused by home appliances recycling in Japan for the period 2001 to 2010 using LCA	EOL analysis shows reduction in GHG emissions after recycling policies are established
Caro et al. (2015)	Country-level consumption behavior in Luxemburg, Italy, has been evaluated using IPCC approach and hybrid LCA modeling; the two approaches were also compared by the authors	It is reported that the country has generated 28,700 Gg CO2e/year for the time period 1995 to 2009, compared to the IPCC inventory IO-based framework showed higher emissions; was concluded that hybrids IO method is more advantageous than IPCC approach
Miller et al. (2005)	Air discharges from purchase of household appliances in the US has been evaluated using EIO LCA	A hypothetical 10,000 US dollar purchase of CEPs results in extremely toxic emissions in their use phase into air which are of potential risk to both consumers and nonconsumers alike
Nakamuraa and Kondo (2004)	Waste input-output model was developed based on hybrid LCA to evaluate the alternate life cycle strategies of domestic appliances; options like recycling according to law, DfES, extension of product life (EPL), Dfd, and treatments like shredding and landfilling were all evaluated	Recycling was reported to reduce Carbon emissions, depletion of abiotic resources, generation of waste, and landfill consumption, provided the rate of retrieval is high; the authors also stated that hybrid LCA was very more easy and effective to model the process compared to the conventional LCA
Alessandra papetti (2014)	Innovations categories are defined for white goods and the environmental impacts are evaluated using LCA	Use phase was reported to be the dominant one, and Oven with nonstick paint was reported to show 15% less energy consumption in this work

3.6. Low-profile electronic products

Table 11. Comparison of LCA studies of low-profile electronic products based on their major focus/contribution and conclusions/findings.

Author	Major contribution/focus of the work	Major findings/conclusions
Yung et al. (2011)	LCA of remote sensor was modeled and eco-design suggestions	Manufacturing was reported as the most dominant phase; the original product and the newly altered product with eco-design strategies were evaluated again using LCA and altered product proved to be environmentally more beneficial
Yung et al. (2008)	LCA of two personal electronic products, namely, heart rate monitor and weather station, was carried out	Raw materials extraction was reported to be the most dominant phase
Muñoz et al. (2008)	LCA of a teddy bear consisting of E& E parts was carried out	Use phase due to battery production was the dominant one
Yung et al. (2012)	Eco-redesign of a heart monitoring sensor was carried out based on LCA, and the new design was compared with the original one	Material extraction was reported as the dominant phase; the new design was reported to create lesser impacts
Park et al. (2007)	Digital camera was assessed using a developed eco-efficiency method based on LCA	Eco-efficiency of cameras with rechargeable batteries is higher the ones with alkaline batteries

4. Systematic literature review

The narrative review above summarized the various ELCA studies published under a wide range of product categories and presented some important findings/major conclusions drawn by various authors. Moving on to the second objective of this work, a systematic review is conducted using standard bibliometric techniques. More specific objectives apart from the ones mentioned in Section 2 are listed as follows:

1. Understand the publication trend in this field of research.
2. Identify the leading journals which publish related work.
3. Explore the research methodologies (RMs) employed until now in order to provide recommendation for future methods and frameworks.
4. Analyze and categorize the overall goal of ELCA employed within different studies and how effectively it has been utilized as a DMT.

4.1. Review methodology

The standard bibliometric techniques followed up-to-date by many authors in management field such as distribution of publications, geographical distribution of authors, top journals that have published related work, and RMs used are followed here as well. In order to conduct this systematic review, we used SCOPUS "the largest data-base of peer-reviewed literature." With information so much excessively available and research becoming more and more global, critical research output with smart tools to track and analyze them is the key toward achieving holistic results. Scopus provides all these facilities and allows deeper analysis from a wide range of literature.

The combination of keywords used to identify the relevant body of work is listed below:

- [Environmental life cycle assessment] AND [Electronic products]
- [Environmental impact assessment] AND [Electronic products] AND [Sustainable]
- [Environmental life cycle assessment] AND [Electronic equipment's]
- [Sustainability] AND [Electronic products]
- [Life cycle assessment] AND [Electronic products]
- [Environmental life cycle assessment] AND [Television]
- [Environmental life cycle assessment] AND [Desktops]
- [Environmental life cycle assessment] AND [Notebooks]
- [Environmental life cycle assessment] AND [Laptops]
- [Environmental life cycle assessment] AND [Computers]
- [Environmental life cycle assessment] AND [ICT]
- [Environmental life cycle assessment] AND [Integrated desktops]
- [Environmental life cycle assessment] AND [Mobile phones]
- [Environmental life cycle assessment] AND [Tablets]
- [Environmental life cycle assessment] AND [Refrigerators]
- [Environmental life cycle assessment] AND [Washing machines]
- [Environmental life cycle assessment] AND [home appliances]
- [Environmental life cycle assessment] AND [AC]
- [Environmental life cycle assessment] AND [Telecommunications]

This investigation helped us identify 1,186 research articles published in various journals related to ELCA and electronic products. We did not wish to restrict the scope of this review within any time frame; however, the search results revealed only articles from the year 1995 through 2015. Only peer-reviewed journal publications were included in this review; conference papers, conference reviews, book chapters, general reviews, dissertations, reports, and other sort of unpublished work were excluded in order to facilitate a more focused review. Also journals are believed to be the most common forum where new findings are published (Ngai, Moon, Riggins, & Yi, 2008). In order to do the bibliometric analysis, the huge literature collection downloaded as a result of combination of keywords search were further refined. The initial search results (Table 12) were distilled, the author reviewed the abstracts of the articles, and the overlapping studies and irrelevant articles were removed and finally a database of 134 articles was constructed. Further each article in this database was carefully read by the author to avoid errors and ensure accuracy in the classifications made, results presented, and future recommendations stated. For this, the author created a spreadsheet to record the basic information of the article like title, authors, region, Journal name, and year of publication as well as LCA-related columns like most relevant impact categories, LCIA methods used, types of LCA

Table 12. Initial search results.

Keywords	Initial search results	Refined results
ELCA & Electronic products	112	46
Environmental impact assessment & Electronic products	12	1
Sustainability & Electronic products	87	2
ELCA & Electronic equipment's	86	4
LCA & Electronic products	138	6
ELCA & TV	40	13
ELCA & desktops	18	3
ELCA & notebooks	4	1
ELCA & laptops	16	6
ELCA & computers	472	8
ELCA & ICT	32	8
ELCA & integrated desktops	3	0
ELCA & Mobile phones	23	12
ELCA & Tablets	8	1
ELCA & Refrigerators	23	6
ELCA & Washing Machine	17	3
ELCA & Home Appliances	14	4
ELCA & AC	14	5
ELCA & CEP	25	1
ELCA & Telecommunications	42	4

involved, most dominant life cycle phases, etc. (Appendix A, found in online supplemental information).

4.1.1. Classification methods

Two kinds of classification frameworks were employed in this review. In the first framework the articles were classified based on six dimensions. The dimensions identified provide a comprehensive analysis of the reviewed articles and also help in achieving objectives 1 & 2 listed in the beginning of this section (Taticchi et al., 2014). Wu et al. (2014) had classified SLCA studies using a framework. The authors of this work have made a few modifications according to the requirement of this review conducted within ELCA studies and used it as the second framework (Fig. 1). The modifications made in our framework are highlighted as follows:

- Addition of categories like Research Purpose, LCIA methods used, and System boundaries involved within the overview of studies.
- Within the subcategory of Comparative Purpose, studies are classified based on product and functional comparison.
- Within the subcategory of Types of approach, modeling, methods, and case study categorization are included.
- Within the subcategory of Data Collection methods, secondary and primary data classification is carried out and within each of those categories, new classifications like Disassembly, Patents, and Archival are included.
- Finally within the subcategory of regional, sector, company, country level, and case analysis are the classifications done.

Figure 1. Framework used for classifying research methodologies (RMs).

Overall, our framework was designed based on 24 criteria which were used to classify the overview of all the ELCA studies (Objectives 3 and 4) included in this review (product categories were excluded, as they are already presented under narrative review).

4.2. Descriptive statistics

In this section first the distribution of articles based on journals, year of publication, and geographical location are presented. Further to which classification of RMs used, data levels and data collection methods are also presented in figures. In the case of RMs used, some studies might have used more than one type of approaches, for instance, modeling & case studies. Results are presented in total numbers and percentages in some cases.

4.2.1. Analysis of publication data (first framework)

Figure 2 presents the time distribution of publications which clearly shows an exponential rise in the number of journal publication in this research area indicating a growing trend. 97 articles (72.38%) were published in the last 10 years.

Table 13 lists the most prolific authors who have been more productive in terms of giving publications in the studied time period in this area of research. Asa Moberg and Roland Hischier lead the list with 10 and 9 publications, respectively,

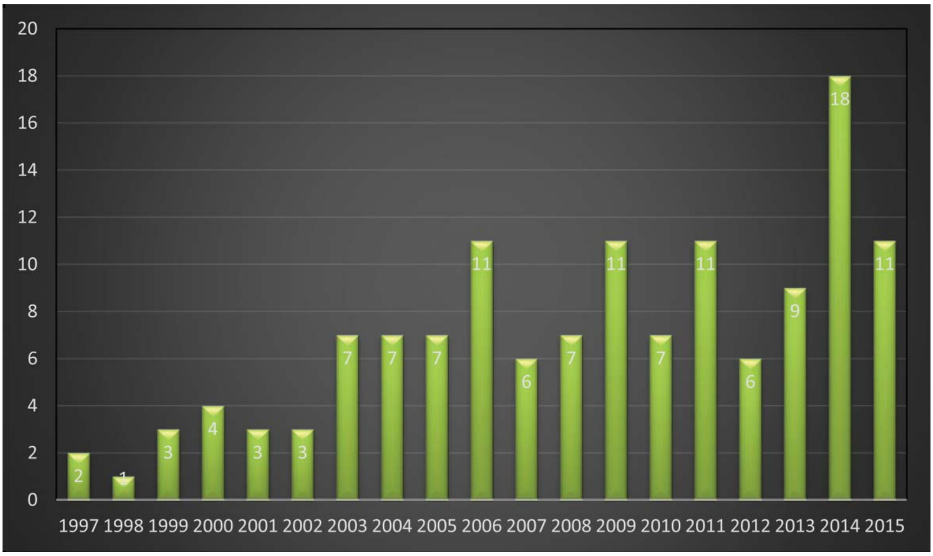

Figure 2. Distribution of articles by year of publication.

followed by Anders S. G, who has given 8 publications. All these mentioned authors are not necessarily the first authors of the work.

Table 14 presents the Top 13 journals which have published articles related to this review. Only journals with more than three related journals are included in the list. *Int J Life Cycle Assess* tops the list with 31 (23.1%) publications followed by *Journal of Cleaner Production* and *Journal of Industrial Ecology* with 14 publications each.

Table 15 lists the top 5 countries that have researched in this area. We further categorized these countries as developed and emerging on the basis of their economies and presented in Fig. 3. Classification reflected that most of the research (71.6%) was carried out in developed countries like the US and the countries in Europe and very less work in (28.3%) in emerging economies among which, scholars in Japan have made most contribution with 18 (47.3%) publications.

Table 13. Author influence.

Authors	Publications
Asa Moberg	10
Roland Hischier	9
Anders S. G	8
Eric Williams	6
Winco K. C. Yung	3
Pil-Ju Park	3
Ester Gutiĕrrez	2
Fernanda Andreola	2
Jonathan G. Overly	2
Y. Barba-Gutiérrez	2
Wolfram Scharnhorst	2

Table 14. Ranking of Journals based on number of publications.

Journals	Publications
Int J Life Cycle Assess	31
Journal of Cleaner Production	14
Journal of Industrial Ecology	14
IEEE	8
Environ. Sci. Technol	7
Resources, Conservation and Recycling	6
Journal of Environmental Management	4
Science of the Total Environment	4
Energy Policy	3
Environmental Impact Assessment Review	3
Journal of Hazardous Materials	3
Waste Management	3
Advances in Intelligent Systems and Computing	3

Table 15. Geography of authors.

Top five countries	Publications
USA	27
Sweden	19
Japan	18
Switzerland	11
Italy	10

Table 16 lists the top five institutions which have contributed in areas related to this review work. Royal Institute of Technology, Sweden, tops the list with 11 publications followed by University of California with 6 publications. Greater contributions have come from Europe followed by the US clearly indicating lack of research interests and articles in developing countries like China, Japan, Hong Kong, India, and other Asian countries in this area of research. Also we realized an interesting fact when we categorized the contribution of organizations in Fig. 4, almost 108 papers (81%) were written by authors associated with universities and only 26 papers (19%) were from nonacademic backgrounds which includes industry, laboratories, recycling centers, and other kinds of research centers.

Figure 3. Types of economies.

Table 16. Top 5 contributing Universities.

Top five Institutes	Publications
Royal Institute of Technology	11
University of California	6
Chalmers University of Technology	4
National Institute of Advanced Industrial Science and Technology	4
The University of Tokyo	4

Figure 5 lists the product categories classified in this work. With no surprise, ICT devices clearly dominate the list with 71 (52.9%) which is more than half the number of publications analyzed in this work, followed by intermediate process with 21 papers. The intermediate processes also involve subproducts and processes of ICT devices only predominantly. Only 5 (0.03%) papers related to low-profile/personal electronic products were published.

Figure 6 presents the classification of ICT devices. From this figure, we can see that desktops and notebooks top the list with 29 publications (40.8%) followed by mobile phones with 16 publications. Online media and Television also had a reasonable share with 14 and 12 publications, respectively.

4.3. Analysis of research methodologies (second framework)

Based on the classification framework presented in Fig. 1, the papers identified were classified in different dimensions.

4.3.1. Different LCA methods

To begin with the different LCA methods that have been used in the papers included in this work are classified and presented in Fig. 7. Full or detailed LCA strictly following ISO 1404X standards topped the list and was used in 103 articles (76.8%). Hybrid LCA, a combination of conventional process-based LCA (P-LCA) and Economic Input Output LCA (EIO-LCA), is gaining more attention and developing in recent times. This approach was used in nine publications.

Figure 4. Contribution of organization.

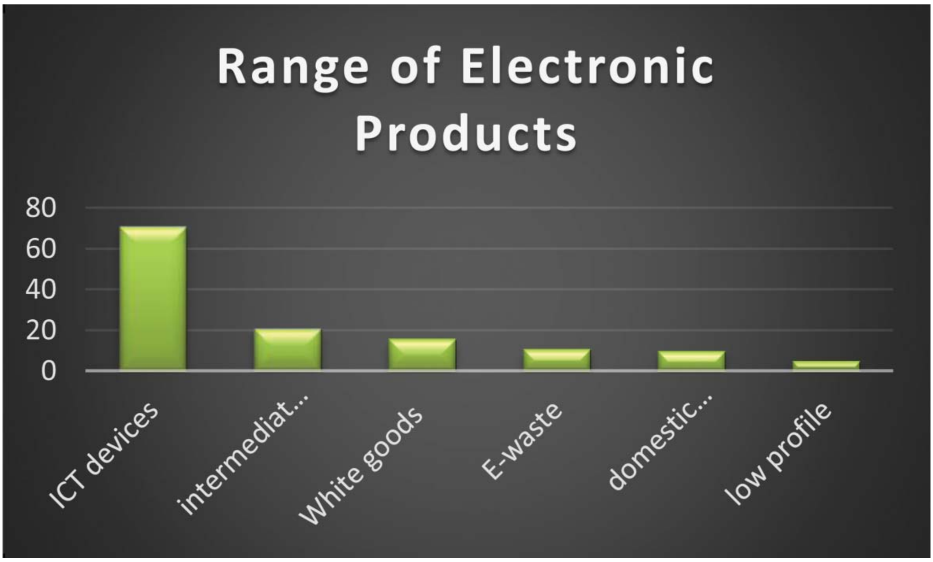

Figure 5. Range of electronic products studied.

Consumption-based LCA was conducted on domestic appliances using this hybrid approach to calculate product energy consumption and impacts, A US household for a 15-year period was taken into account for LCA modeling in this work (Ryen et al., 2015). This approach is mainly used in domestic appliances and intermediate processes and was used only once to assess desktop computer with 17′ CRT monitor (Williams, 2004).

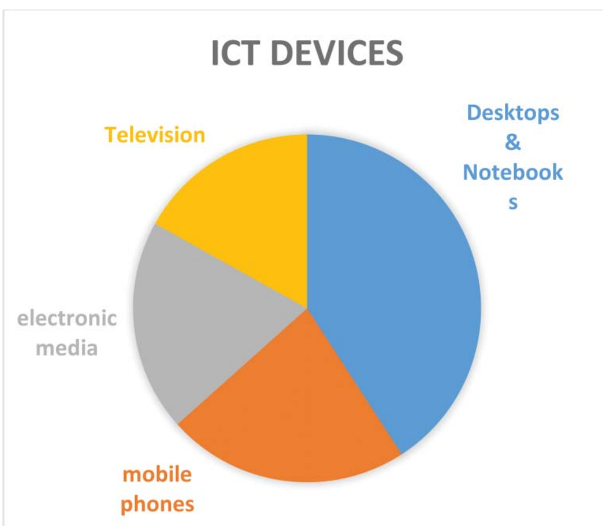

Figure 6. ICT devices.

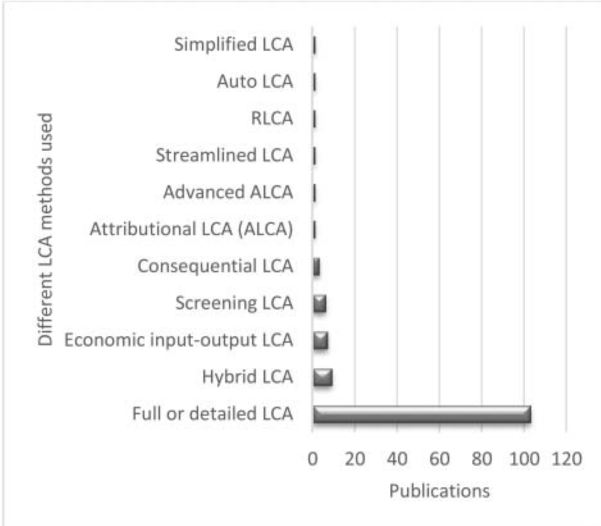

Figure 7. Types of LCA used. Hybrid LCA: Caro et al. (2015), Deng et al. (2011), Eun et al. (2009), Lankey and McMichael (2000), Moberg et al. (2014), Nakamuraa and Kondo (2004), Ryen et al. (2015), Vasan et al. (2014), Williams (2004); Economic input-output LCA: Gay et al. (2005), Norris et al. (2003), Scott Matthewsa et al. (2002), Junnila (2008), Miller et al. (2005), Sarah Boyd and Dornfeld (2011), Teehan and Kandlikar (2013); Screening LCA: Andrae and Andersen (2011), Borggren et al. (2011), Finnveden (2011), Hochschorner et al. (2015), Moberg et al. (2010), Moberg et al. (2010); Consequential LCA: Andrae et al. (2007), Ekvall and Andrae (2005), Huulgaard et al. (2013); AALCA: Andrae (2014); streamlined LCA: Schneider et al. (2008); Reverse LCA (R-LCA): Graedel (1997); Auto LCA: Hossain et al. (2014); simplified LCA: Hur et al. (2005). Note: The papers under each category for Figs. 7–14, 17, and 18 are mentioned below the corresponding figures using the matching reference citations. The categories with less than 30 papers only are mentioned considering space. The references are also marked in the Section 3, where these papers are originally cited Tables 2–11 in order to establish a link.

EIO LCA was used in seven papers and the Screening LCA which is conducted to get quick results was used in six papers. Two interesting approaches that we identified was the auto LCA and Fire LCA.

Auto LCA was used to develop a conceptual framework using clustering and classification and the authors also provided suggestions for sustainable design, and the developed framework was used to conduct case studies using PCB, desktop computers and two kinds of printers, carbon footprint (CF) was assessed. The % reduction of CF before and after using this framework was also compared; the sustainable design incorporated showed reduction in CF. Auto LCA employed proved to reduce efforts taken in assessing the environmental impacts of products based product BOMs which is the conventional route (Hossain et al., 2014).

The fire LCA model described was first of its kind implemented on a TV to compare high- and low-level fire safety based on the flame retardant plastics used in the TV (Margaret Simonson, 2002). Reverse LCA (R-LCA) was conducted on WM to calculate environmental impacts and hot spots identification, the authors claim that this approach has the potential to create an ideal green product (Graedel, 1997).

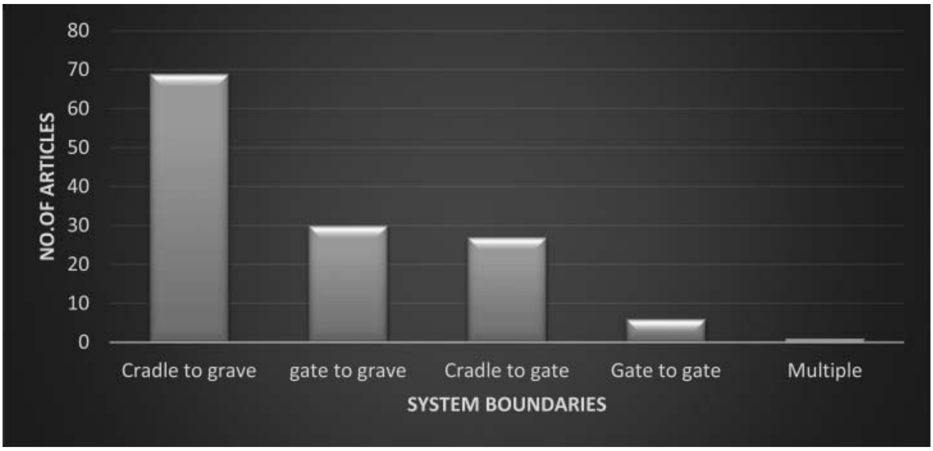

Figure 8. System boundaries. Cradle to grave: Achachlouei and Moberg (2015), Alessandra Papetti and Mandolini, (2014), Anders et al. (2004), Anders et al. (2000), Andreola (2005), Ardente and Mathieux (2014), Barba-Gutiérrez et al. (2008), Borggren et al. (2011), Caro et al. (2015), Choi et al. (2004), Cullen and Allwood (2009), Daiyue et al. (2015), Duan et al. (2009), Ekvall and Andrae (2005), Elduque et al. (2014), Faist Emmenegger et al. (2004), Feng and Ma (2009), Finnveden (2011), Gheewala and Nielsen (2003), Graedel (1997), Grignon-Massé et al. (2011), Hischier and Hischier (2003), Hischier, 2014 (2015), Hischier, et al. (2014), Hischier and Baudin (2010), Hossain et al. (2014), Hur et al. (2005), Huulgaard et al. (2013), Iakovou et al. (2009), Junnila (2008), Yanagitani and Kawahara (2000), Yokota et al. (2003), Maga et al. (2012), Malmodin et al. (2010), Margaret Simonson and Stripple (2002), Socolof et al. (1999), Masafumi Tekawa and Inaba (1997), Lankey and McMichael (2000), Mirabella et al. (2013), Moberg et al. (2010), Muñoz et al. (2008), Nakamuraa and Kondo (2004), Park et al. (2006), Parsons (2006), Pascal De Langhe and Ceuterick (1998), Sarah Boyd and Dornfeld (2011), Satoshi Oikawa and Kensuke (2005), Kim et al. (2001), Schneider et al. (2008), Frey et al. (2006), Socolof et al. (2005), Song et al. (2012), Song et al. (2012), Streicher-Porte et al. (2009), Stutz and O'Connell (2010);Tasaki et al. (2013), Coroama et al. (2014), Vasan et al. (2014), Weber (2012), Xiao et al. (2015), Yang et al. (2004), Yu et al. (2010), Yung et al., 2011, 2008 (2012). Gate to grave: Alston and Arnold (2011), Andreola et al. (2006), Barba-Gutiérrez et al. (2008), Biganzoli et al. (2015), Bigum et al. (2012), Mayers et al. (2005), Dodbiba et al. (2008), Gutiérrez et al. (2009), Dodbiba et al. (2007), Gamberini et al. (2010), Gutiérrez et al. (2010), Hibbert and Ogunseitan (2014), Huisman et al. (2002), Lim and Schoenung (2010), Menikpura et al. (2014), Moraes et al. (2014), Nakano et al. (2006), Niu et al. (2012), Noon et al. (2011), Park et al. (2006), Rocchetti and Beolchini (2014), Rubin et al. (2014), Techato et al. (2009), Wager et al. (2011), Zhang et al. (2004), Zink et al. (2014). Cradle to gate: Andrae (2014), Andrae and Andersen (2011), Andræ et al. (2005), Andrae et al. (2007), Andrae et al. (2004), Dahlben et al. (2013), Eun et al. (2009), Taiariol et al. (1999), Gay et al. (2005), Norris et al. (2003), Gard and Keoleian (2003), Lee and Park (2001), Liu et al. (2014), Miller et al. (2005), Moberg et al. (2014, 2010), Monfared et al. (2014), Park et al. (2007), Ryen et al. (2015), Scharnhorst et al. (2005), Scharnhorst et al. (2006), Shah et al. (2008), Tagami and Williams (2003), Teehan and Kandlikar (2013), Thomas et al. (2011), Williams (2004), Zhou and Schoenung (2007). Gate to gate: Christopher Ciantar (2000), Hochschorner et al. (2015), Kang et al. (2013), Lu et al. (2006), Malmodin et al. (2014), Schien et al. (2013); Multiple: Herrmann et al. (2004).

A simplified LCA was developed by the authors and evaluated using cell phones and vacuum cleaners to identify hotspots in the entire life cycle. The usefulness of the developed method was also compared with the conventional method of ecodesign (Hur et al., 2005).

4.3.2. System boundaries

The classification results based on System boundaries is presented in Fig. 8. Most of the LCAs conducted (69 publications) have used cradle-to-grave assessment (considering all the life cycle stages). Cradle-to-gate and Gate-to-grave assessments have been carried out almost in equal number of publications (27 and 30 publications each). Gate-to-grave assessments mainly include EOL processes in the published articles. Multiple, meaning a cradle to gate (material extraction phase) and gate to grave (material recovery phase), assessments have been carried out within the EOL processes in one of the published works (Herrmann, 2004).

4.3.3. Data collection methods

With regard to data used (Fig. 9), to no surprise secondary data have been widely used by authors to perform LCA (93 publications, around 70% of the reviewed papers) and only 6 publications have used primary data. The few publications which have used primary data do not include any influential ICT device. Inventory collection from telephone exchange (Taiariol et al., 1999), Italian public administration office (Mirabella et al., 2013), LCA conducted on SIP switch product, WM, refrigerators,

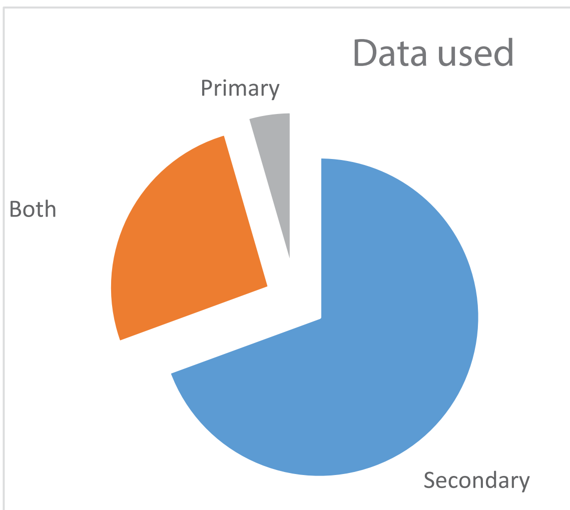

Figure 9. Data used. Primary data: Andrae et al. (2004), Taiariol et al. (1999), Menikpura et al. (2014), Mirabella et al. (2013), Park et al. (2006), Xiao et al. (2015); Both: Alston and Arnold (2011), Anders et al. (2000), Biganzoli et al. (2015), Borggren et al. (2011), Choi et al. (2004), Deng et al. (2011), Duan et al. (2009), Faist Emmenegger et al. (2004), Finnveden (2011), Gay et al. (2005), Hibbert and Ogunseitan (2014), Huulgaard et al. (2013), Kang et al. (2013), Yanagitani and Kawahara (2000), Yokota et al. (2003), Lee and Park (2001), Liu et al. (2014), Malmodin et al. (2014), Margaret Simonson and Stripple (2002), Moraes et al. (2014), Muñoz et al. (2008), Park et al. (2007), Pascal De Langhe and Ceuterick (1998), Schien et al. (2013), Kim et al. (2001), Socolof et al. (2005), Song et al. (2012, 2012), Stutz and O'Connell (2010), Teehan and Kandlikar (2013), Weber (2012), Yang et al. (2004), and Yung et al. (2011, 2008, 2012).

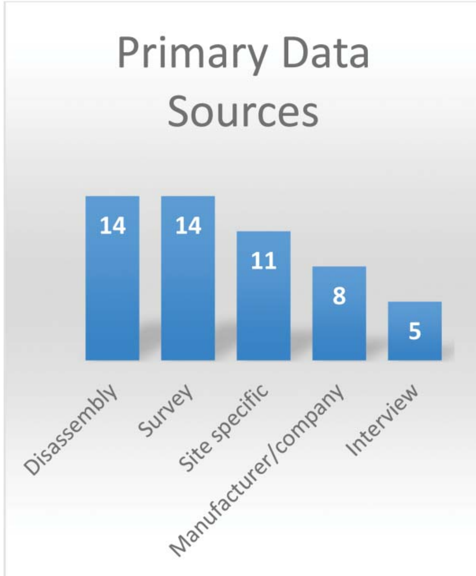

Figure 10. Primary data sources. Disassembly: Alston and Arnold (2011), Anders et al. (2000), Andrae et al. (2004), Deng et al. (2011), Taiariol et al. (1999), Hibbert and Ogunseitan (2014), Huulgaard et al. (2013), Kang et al. (2013), Moraes et al. (2014), Muñoz et al. (2008), Pascal De Langhe and Ceuterick (1998), Song et al. (2012), Stutz and O'Connell (2010), Teehan and Kandlikar (2013), Weber (2012), Survey: Choi et al. (2004), Duan et al. (2009), Faist Emmenegger et al. (2004), Gay et al. (2005), Lee and Park (2001), Margaret Simonson and Stripple (2002), Park et al. (2006); Site specific: Anders et al. (2000), Yanagitani and Kawahara (2000), Liu et al. (2014), Park et al. (2007), Kim et al. (2001), Socolof et al. (2005), Song et al. (2012), Xiao et al. (2015), Yung et al. (2012); Manufacturer/company: Menikpura et al. (2014), Schien et al. (2013), Malmodin et al. (2014), Borggren et al. (2011), Finnveden (2011), Biganzoli et al. (2015), Yang et al. (2004); Interview: Yokota et al. (2003), Mirabella et al. (2013), and Yung et al. (2008, 2011).

and WEEE (recycling) have used primary data for LCA modeling. Further the data collection methods employed by the authors for LCI were also analyzed and classified.

The data sources are presented for primary and secondary data separately in Figs. 10 and 11, respectively. Disassembly and Survey dominate the list in primary data sources with 14 publications each, authors have used these data sources to primarily conduct LCA of ICT devices (23 publications) followed by low-profile products, intermediate processes, and white goods (18 publications). Databases which come with the software toolkit like Eco Invent dominate the list of secondary data sources(71 papers) followed by published literature (48 papers). Archival data in the form of publicly available records or reports or government year book statistics were also used in 38 publications.

4.3.4. Data-analysis level

Further the data levels are also analyzed for the publications reviewed in this work, based on which the results are presented in Fig. 12.

Case analysis dominated the list with 77 papers, of which multiple products and processes were analyzed in 63 studies and unit process-level analysis, meaning one

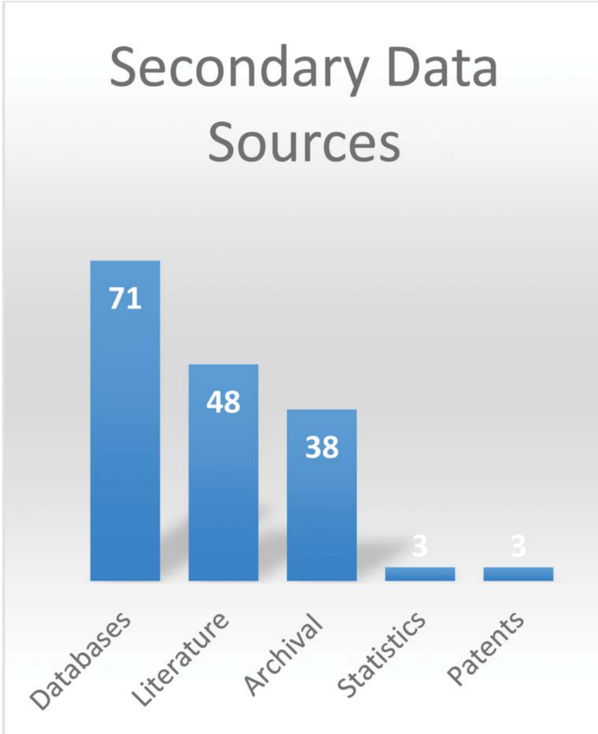

Figure 11. Secondary data sources. Archival: Anders et al. (2000), Andræ et al. (2005), Andreola (2005), Andreola et al. (2006), Barba-Gutiérrez et al., (2008), Mayers et al. (2005), Choi et al. (2004), Duan et al. (2009), Gutiérrez et al. (2009), Faist Emmenegger et al. (2004), Gay et al. (2005), Norris et al. (2003), Gutiérrez et al. (2010), Scott Matthewsa et al. (2002), Hischier and Hischier (2003), Malmodin et al. (2010), Lankey and McMichael (2000), Miller et al. (2005), Moberg et al. (2010), Muñoz et al. (2008), Park et al. (2006), Ryen et al. (2015), Kim et al. (2001), Frey et al. (2006), Tagami and Williams (2003), Tasaki et al. (2013), Coroama et al. (2014), Williams (2004), Yu et al. (2010), Statistics: Caro et al. (2015), Daiyue et al. (2015), Nakano et al. (2006); Patents: Hischier (2014), Margaret Simonson and Stripple (2002), and Sarah Boyd and Dornfeld (2011).

single phase like EOL, production or manufacturing, or use of products was assessed in 14 publications. In one of the studies in this category, a multivariate data analysis method was followed to reduce the difficulties in handling a complex data set; the authors had used principal component analysis and multidimensional scaling to address this issue and the product category analyzed was domestic appliances using secondary data for EOL phase only (Gutiérrez et al., 2010).

Country-level analysis was carried out for various products in 42 papers. Japan topped the list of countries; however most of the publication were very old and the most recent publication was in 2013 (Tasaki et al., 2013). The next country in the list was the US with more recent five publications.

Company-level analysis was carried in eight papers, the companies include Motorola, Fujitsu, DELL, and Philips to name a few and all this analysis was carried out on ICT devices. Regional-level analysis covering few regions in the US, China, the UK, and Italy was also done in five papers. Sector-level analysis which

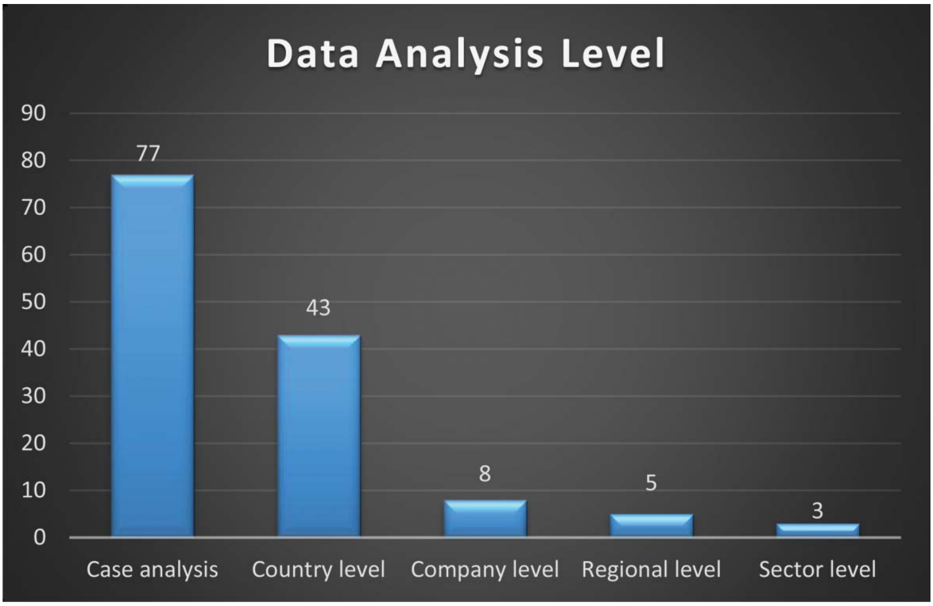

Figure 12. Data analysis level. Case analysis (Unit process level): Alston and Arnold (2011), Andræ et al. (2005), Andrae et al. (2004), Andreola et al. (2006), Bigum et al. (2012), Deng et al. (2011), Dodbiba et al. (2008), Dodbiba et al. (2007), Park et al. (2006), Rocchetti and Beolchini (2014), Rubin et al. (2014), Williams (2004), Zhang et al. (2004), Zink et al. (2014). Country level: China: Duan et al. (2009), Niu et al. (2012), Song et al. (2012), Xiao et al. (2015), Yu et al. (2010); Switzerland: Faist Emmenegger et al. (2004), Moberg et al. (2010), Scharnhorst et al. (2005, 2006), Wager et al. (2011); USA: Scott Matthewsa et al. (2002), Noon et al. (2011), Ryen et al. (2015); Company level: Gay et al. (2005), Huisman et al. (2002), Junnila (2008), Satoshi Oikawa and Kensuke (2005), Schien et al. (2013), Weber (2012), Yang et al. (2004); Regional level: Barba-Gutiérrez et al. (2008), Mayers et al. (2005), Daiyue et al. (2015), Miller et al. (2005), Shah et al. (2008); Sector level: Norris et al. (2003), Malmodin et al. (2010), and Mirabella et al. (2013).

included electronic computer sector (Norris et al., 2003), E & M sector (Malmodin et al., 2010) and ICT devises in tourism sector (Malmodin, Lundén, Moberg, Andersson, & Nilsson, 2014) was carried out in 3 publications.

4.3.5. Different LCIA methods used

In some papers, the LCIA methods employed and software packages used are not clearly reported by the authors. Figure 13 presents the different LCIA methods used in the studies. Eco-indicator was the most used (28 papers), followed by CML method. Multiple assessment methods were used in eight publications. Recipe method which is gaining more significance recently has been used only in six studies (all of which were published in 2014 & 2015). Interestingly the author who has most used Recipe method is Roland Hischier, who is one the prolific authors in the research area studied here. IPCC has been used in papers where single category like CF was assessed and excel-based methodology based on LCA guidelines was also employed in one of the publications (Maga et al., 2012) to compare two ICT

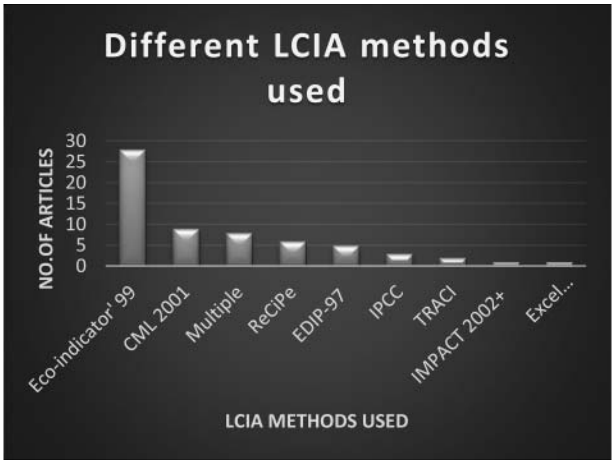

Figure 13. Different LCIA methods used. CML: Liu et al. (2014), Moberg et al. (2010), Muñoz et al. (2008), Pascal De Langhe and Ceuterick (1998), Rocchetti and Beolchini (2014), Kim et al. (2001), Schneider et al. (2008), Xiao et al. (2015), Zink et al. (2014); Multiple: Alston and Arnold (2011), Hischier and Hischier (2003), Kang et al. (2013), Lee and Park (2001), Moberg et al. (2014), Moberg et al. (2010); Recipe: Hischier, 2014 (2015), Hischier et al. (2014), Hishier (2015), Hochschorner et al. (2015); EDIP: Bigum et al. (2012), Moraes et al. (2014), Rubin et al. (2014), Techato et al. (2009), Yang et al. (2004); IPCC: Nakano et al. (2006), Noon et al. (2011), and Teehan and Kandlikar (2013); Excel: Maga et al. (2012).

solutions, desktops, and thin client computing in Germany; however, only GWP was assessed in this work.

4.3.5.1. Impact categories assessed. Figure 14 presents the impact categories assessed in the papers considered for this review. Single impact category was assessed in 22 studies, GWP was the most assessed single indicator except one study in which direct land use (DLU) was assessed (Sibylle D. Frey, 2006). A couple of impact categories were assessed in 13 publications, most commonly used indicators were GWP and CED. Multiple environmental impact categories were assessed in 99 papers.

Further among the multiple categories assessed, the most relevant impact category which created significant negative impacts were also classified. The classification results are presented in Table 17. Since different LCIA methods are used in different papers, the results reported by the authors are categorized according to the midpoint and end point indicators. GWP tops the list with 30 papers followed by CED in 12 papers. Direct Land Use has been assessed and reported only in three papers. Categories which have been assessed in three or more publications are only listed here. Within end point indicators, damage to ecosystem quality and human health has been equally done (25 and 23 papers, respectively).

4.3.5.2. Life cycle stage that needs attention. Among the various life cycle phases studied in a product life cycle, a few phases only create more environmental impacts, and such phases need attention in order to mitigate the impacts created.

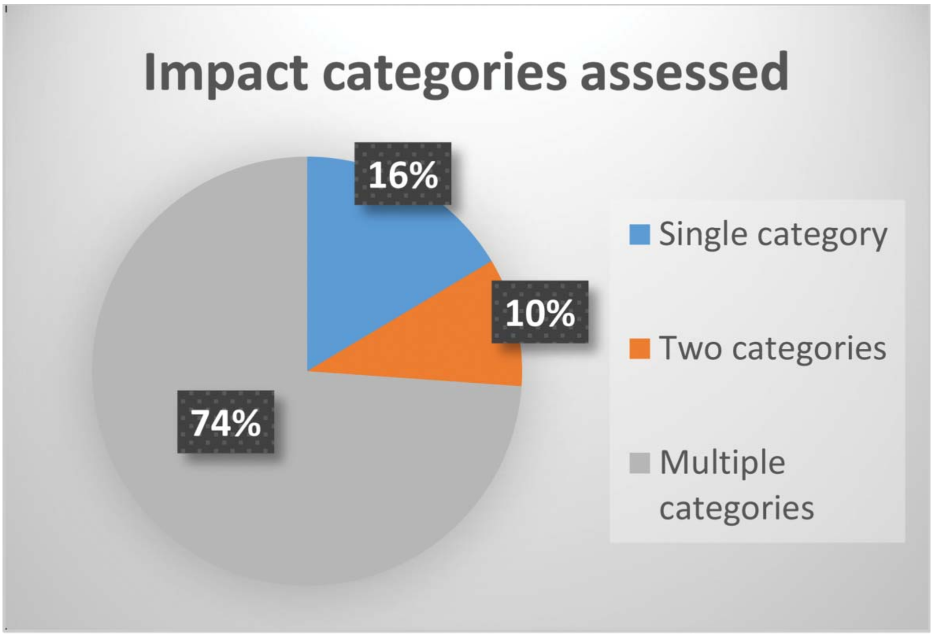

Figure 14. Impact categories assessed. Single impact: Andrae (2014), Andrae and Andersen (2011), Andræ et al. (2005), Caro et al. (2015), Ekvall and Andrae (2005), Norris et al. (2003), Hochschorner et al. (2015), Hossain et al. (2014), Yokota et al. (2003), Maga et al. (2012), Malmodin et al. (2010), Menikpura et al. (2014), Nakano et al. (2006), Noon et al. (2011), Satoshi Oikawa and Kensuke (2005), Frey et al. (2006), Stutz and O'Connell (2010), Coroama et al. (2014), Teehan and Kandlikar (2013), Thomas et al. (2011), Vasan et al. (2014), Weber (2012); Two impacts: Andrae et al. (2004), Herrmann et al. (2004), Daiyue et al. (2015), Deng et al. (2011), Dodbiba et al. (2007), Grignon-Massé et al. (2011), Huulgaard et al. (2013), Kandlikar and Teehan (2011), Malmodin et al. (2014), Lankey and McMichael (2000), Moberg et al. (2010), Tasaki et al. (2013), and Williams (2004).

Figure 15 presents the life cycle phases that were reported to have created most environmental impacts in the LCA studies reviewed in this work. Few authors have not given any conclusion in this regard owing to allocation procedures and assumptions made. Based on the results that were reported, use phase clearly dominates the list with 37 papers followed by production and EOL phases with 25 publications each. Distribution, packaging, and assembly have created less impact relatively. Within the 37 papers which reported use phase as the dominant phase,

Table 17. Most relevant impact categories.

Midpoint	Publications	Endpoint	Publications
Global warming	30	Human health	23
Cumulative Energy Demand (Dobon et al.)	12	Ecosystem quality	25
Ozone layer depletion (ODP)	11	Resources	12
GHG emissions	10		
Acidification (AC)	7		
Eutrophication (EP)	7		
Abiotic Resource depletion (ADP)	6		
Fossil Fuel depletion (FD)	4		
Direct Land Use	3		

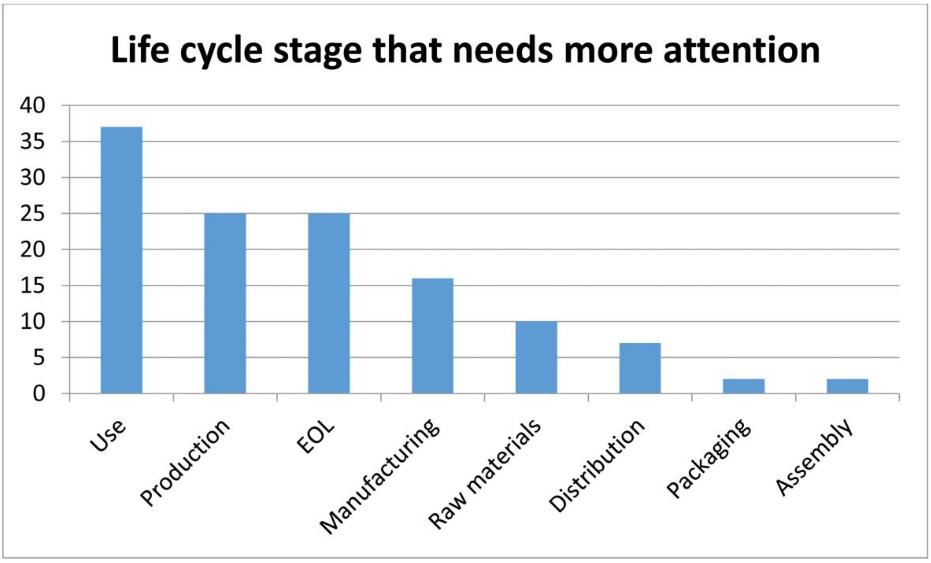

Figure 15. Life cycle stage that needs attention.

13 papers were LCA studies on ICT devices. Also none of these studies have used primary data sources for LCA modeling, which implies the reported results are based on assumptions made. Similar is the case for production phase also, only three studies have used primary data sources partly.

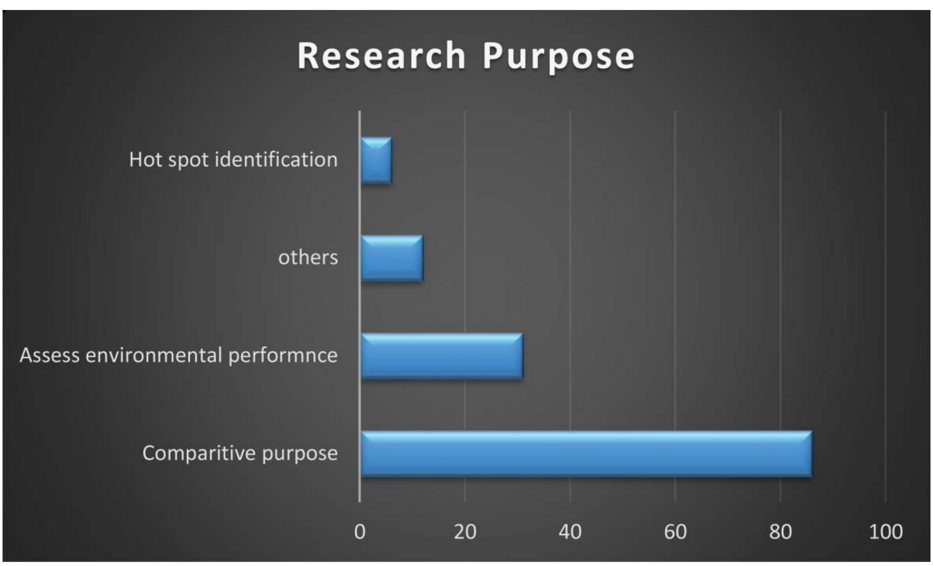

Figure 16. Research purpose.

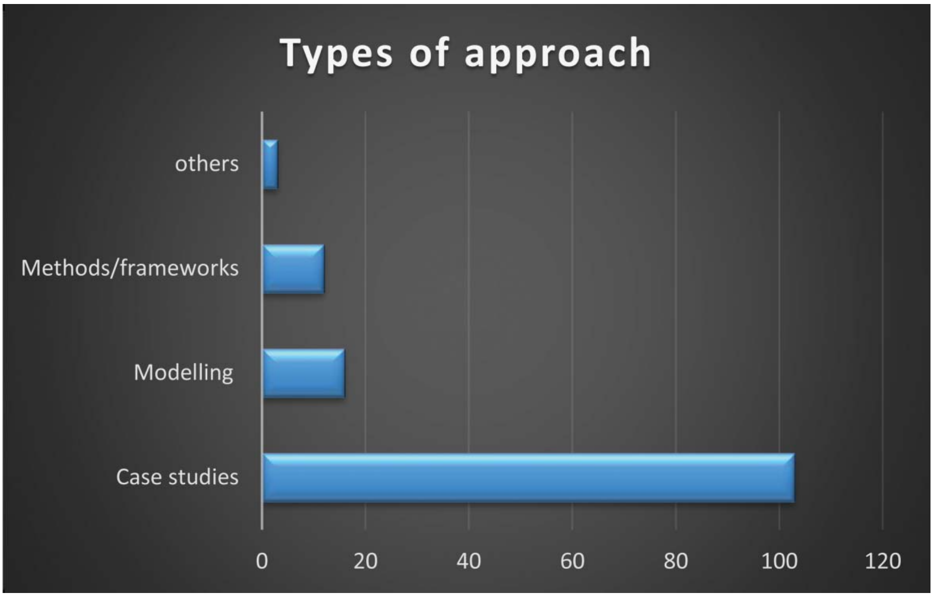

Figure 17. Types of approach. Modeling: Anders et al. (2004, 2000), Andræ et al. (2005), Andrae et al. (2004), Barba-Gutiérrez et al. (2008), Laurenti et al. (2014), Margaret Simonson and Stripple (2002), Lankey and McMichael (2000), Park et al. (2006), Park et al. (2006), Ryen et al. (2015), Kim et al. (2001), Streicher-Porte et al. (2009), Teehan and Kandlikar (2013), Williams (2004), Zhou and Schoenung (2007); Frameworks: Alessandra Papetti and Mandolini (2014), Andrae (2014), Ardente and Mathieux (2014), Daiyue et al. (2015), Deng et al. (2011), Eun et al. (2009), Hossain et al. (2014), Hur et al. (2005), Iakovou et al. (2009), Liu et al. (2014), Nakamuraa and Kondo (2004), and Park et al. (2007).

4.3.6. Overall goal

Based on the framework presented in Fig. 1, the overall goals of the studies were classified based on the research purpose (Fig. 16) and types of approaches (Fig. 17) employed to achieve the same were also classified.

4.3.6.1. Research purpose. Within this category, three major purposes, namely, hot spots identification, comparative purpose, and assessing environmental performance were identified; the rest were classified as others. The overall goal of LCA in most of the studies was for comparative purpose (86 papers) which is 64% of the papers reviewed in this work. So in all these studies in addition to assessing environmental impacts of products, the goal was to compare the products or their functions. Hence there was a need to further classify this sub-category to understand what kind of comparisons have been carried out (Fig. 18).

In most papers products, processes, or systems were compared (47 papers, 55%). The comparisons in this category is mainly between the print and tablet version of newspapers, movies, eBooks, and normal books. Comparison between different displays (CRT, LCD, and Plasma) was also carried out by many authors. A few studies also included comparison between desktop and laptops, 2G and 3G mobile phones, and between battery systems.

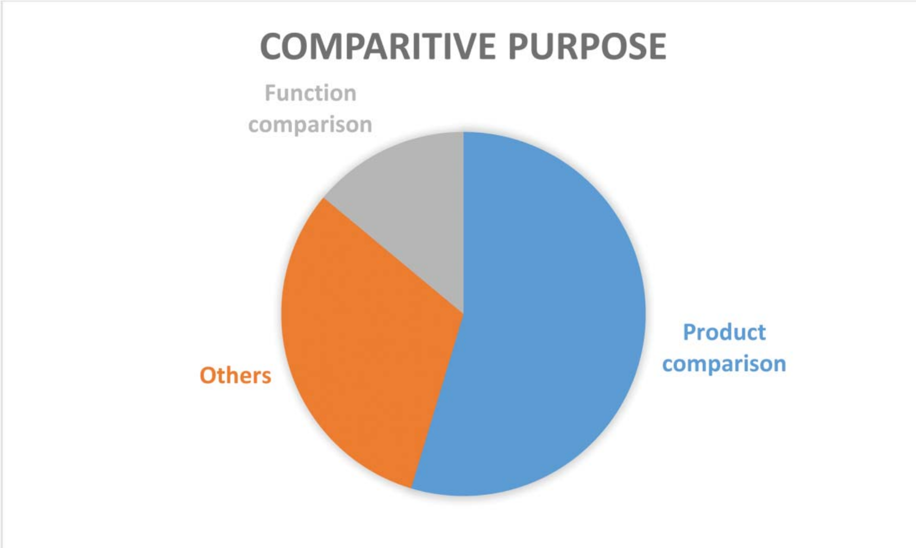

Figure 18. Comparative purpose. Function comparison: Alessandra Papetti and Mandolini (2014), Andreola (2005), Andreola et al. (2006), Ardente and Mathieux (2014), Hossain et al. (2014), Margaret Simonson and Stripple (2002), Menikpura et al. (2014), Pascal De Langhe and Ceuterick (1998), Satoshi Oikawa and Kensuke (2005), Yung et al. (2011), Yung et al. (2012), Zink et al. (2014); Other comparisons: Alston and Arnold (2011), Andrae (2014), Caro et al. (2015), Mayers et al. (2005), Christopher Ciantar (2000), Cullen and Allwood (2009), Daiyue et al. (2015), Dodbiba et al. (2008), Eun et al. (2009), Dodbiba et al. (2007), Gamberini et al. (2010), Hishier (2015), Hur et al. (2005), Lee and Park (2001), Malmodin et al. (2010), Miller et al. (2005), Moberg et al. (2014), Moraes et al. (2014), Nakano et al. (2006), Park et al., 2006 (2006), Rocchetti and Beolchini (2014), Rubin et al. (2014), Kim et al. (2001), Shah et al. (2008), Streicher-Porte et al. (2009), Wager et al. (2011).

Function comparison was carried out in 12 publications. Within this category most of the comparisons were carried out between the original and new version of the product with eco-design suggestions or made of recycled materials or same products manufactured with time gaps. Also reuses options for the same product and different lifetimes of the same product were compared in some cases.

Other types of comparisons were carried out in 27 papers. Within this category, comparison between LCA and other approaches, between different scenarios and methods involved in waste management & EOL phase overall, between 2 sectors, between different LCIA methodologies for the same product, between LCA methods and models, between product components, and between perspectives of different user categories are some examples. Processes, scenarios, recycling options, and others related to EOL phase clearly dominate this comparison category.

4.3.6.2. Types of approach. In order to achieve the research purpose or goal of the study, the individual authors of different studies had employed a few approaches which were classified based on the few categories identified. Case studies clearly dominate this list with 103 publications (76.8%). Within this category most of the authors have used LCA to assess single electronic product or compare different products/product groups, following the conventional methodological framework and reported their findings.

Next in the list is the modeling approach with 16 papers. In this category, consumption weighed LCA modeling was carried out on domestic appliances at country level (Ryen et al., 2015). Data envelope analysis based eco-efficiency model (Barba-Gutiérrez et al., 2008), combination of top-down and bottom-up approaches (Park et al., 2005), environmental and economic aspects were integrated in a model by a few authors, a model for LCI data collection was also developed (Andræ, 2004), few models combined existing LCAs, addressed uncertainties involved, integrated LCA and quality function deployment.

The next type of approach used was methods or conceptual frameworks (12 papers); within this category, simplified LCA methods, methods to address uncertainties in LCA, multicriteria matrix method, method to assess the durability of energy using products, method based on spatial environmental balance (SEB) (Daiyue et al., 2015), and advance ALCA method (Andrae, 2014) are some examples. Statistical approaches used in two papers were classified within the category others. Generally LCA is a very data-intensive analysis tool, so the authors used multidimensional scaling technique (MDS) to reduce the dimensionality of the large data sets involved in LCA of domestic appliances (Gutiérrez et al., 2009).

5. Current trends and discussion

Two very important goals of an effective literature review are to first integrate and summarize what is known in an area and second to learn from others and stimulate new ideas (Neuman, 2000). In this work we have conducted a narrative and systematic review of journal publications in the area of ELCA & electronic products. We used narrative literature review to present some important findings and results of the past and current research in this area within various product categories identified. We employed systematic review to classify the publications into identified research domains, critically evaluate the studies in terms of data levels and data collection methods, and finally interpret the findings in order to understand the research trends as well as the usefulness of LCA as a DMT.

LCA has received quite a lot of attention within the electronics industry. In this work a database of 134 publications relevant to this review work were identified from 43 journals within the time period 1995 to 2015, though this is not a very exhaustive list, but is definitely a comprehensive list reflecting the existing body of work in this research area and does highlight several important inferences.

5.1. Research trends

The rate of growth of publications in this area is quite evident especially in the last year. Despite LCA's long history its usage in electronics industry jumped off only a decade back. Hence this definitely is the future and more research work and publications will increase in the coming years. Most of the researches are carried out in developed economies, though Japan, an emerging economy has made a good number of contributions in this research area, the list does not include very recent publications.

The lead Journal that has published a good number of papers in this area is related to LCA. As we can see that life cycle thinking is being introduced in every product nowadays owing to various reasons including consumer awareness toward eco-friendly products, EU directives marketing tactics to brand their product as green and many more. Given with this situation, we should expect to see more papers in this area getting published in management and business related journals as well in the future.

Two of the lead authors who were identified prolific in this area have environment strategies related background and the second most prolific author was found to have nano science background. So going forward researchers from a wide range of academic background will enable create new dimension to LCA studies.

5.2. Most and least researched products

As was demonstrated in the narrative review, ICT devices have received more attention by the scholars in this area. One can understand that technology is driving this world at an unimaginable pace, however damage created by other range of products cannot be ignored and taken lightly. Peer-reviewed journal publications related to low-profile electronic products like vacuum cleaners, benders, microwave ovens, cameras, set top box and many more such products which are essential commodities in every household has to be assessed. Though as single commodity they might produce less impact, their cumulative effect when considered as an entire household CEP and further as a community, or region will be very major. Also intermediate processes and products have received less scholarly attention.

Within the white goods refrigerators and WM created more impacts relatively (Gutiérrez et al., 2010). Also magnetic refrigeration showed higher impacts compared to vapor compression refrigerator, owing to the rare earth metals into the magnet (Monfared et al., 2014). Hermetic compressor was found to contribute more to impacts in LCA study of refrigerators (Christopher Ciantar, 2000). Replacing HCFC22 with HFC410A for the refrigerant proved to be eco-friendly option in terms of GWP (Yanagitani and Kawahara, 2000). Effects of treatment of small components of **AC** in waste stream are very critical and when considered at national level will result in huge impacts (Techato et al., 2009). Laurent Grignon-Masse et al. (Grignon-Massé et al., 2011) also confirmed through their LCA study that for energy-efficient ACs the focus must be on working fluid leakage. Centralized systems were considered to be more superior that individual ones in terms of impacts created (Gheewala and Nielsen, 2003). Inverse washing machine effect was demonstrated in a study where the over emphasis given to the use phase leaving out the other phases like transportation which must have been more significant outside the boundary and its effects was demonstrated, by doing this the authors emphasized on prioritization for LCA practitioners for best result and avoid double counting of any phase impacts (Cullen and Allwood, 2009). Eco-mouse (Schneider et al., 2008) and oven with nonstick coating (Alessandra papetti, 2014) were some innovative strategies used by authors to reduce environmental impacts.

Within mobile phones, GSM and UMTS networks results in negative impacts, especially the transition phase has to be short to reduce more damage (Scharnhorst et al., 2006). Energy use and 3G mobile network service providers are biggest contributors toward service footprint and data centers are given more attention than what is required and researchers need to concentrate more on entire system for evaluation of footprints rather than fractions (Schien et al., 2013).

5.3. Life cycle phases assessed

When product life cycle phases are analyzed for electronic products, the use phase, EOL phase, and production phases are reported as dominant. But is it actually true? Use of an electronic product is determined by its power requirement for operation, usage patterns, and life span of the product (*Environmental assessment of consumer electronic products*, 2010). All these three factors are interlinked, and the usage pattern is determined by the consumer exclusively, but in all the studies only assumptions are made regarding the life span of the product, standby mode of the device, and effective use time of the device. User phase is very critical for any energy using product, both methodological and practical studies to determine future behavior of users as well as what a customer values most have to be considered in LCA modeling and dichotomy between theory and practice and industrial applications of LCA has to be more user-friendly by combining EIO and process LCA (Junnila, 2008).

Even the battery usage and solar power usage assumptions made have to be checked (Zink et al., 2014). Data collection for intermediate products and processes and LCA of those are very essential when assessing complex ICT products, LCI for recycling option in that region can also be done, all of this will give more realistic results (Anders S. G. Andræ, 2004; Andræ et al., 2005). A notion that replacing an old product with a new energy-efficient product in the market is an eco-friendly option was evaluated using an assessment approach by the authors, and concluded that replacement of refrigerator does not change the results much, but replacement of TVs is beneficial, however in future the authors recommend to test this using more impact factors (Tasaki et al., 2013).

In the EOL phase, only assumptions are made for what the consumer does with the product after its EOL. Changes in the usage of ICT devices were analyzed in three different perspectives ranging from individual devices to global sales of desktop, laptop and tablet computers and were compared. Also the authors primarily answered the questions of which effect actually dominates the environmental impacts: increase in energy efficient product and technology or the increase in number ICT devices and higher usage rate? (Hishier, 2015). Hence assumptions is use phase have to be genuine. Specific data for energy use during use phase and production phase were highly recommended; primary data for key components like ICs and process-specific data like raw material acquisition of metals like gold and air transportation were emphasized for collection of primary data (Moberg et al., 2014). Surveys can be conducted in particular regions and can be used to model the use and EOL more realistically for a particular product. Similarly the overall energy termed as gray energy was evaluated using LCA (Hischier, 2015). The authors also stated that production phase has to be evaluated fully for its energy consumptions and data transfer when using Internet has to be also evaluated.

In the EOL phase according to the recycling systems established in each country, different scenarios can be modeled using LCA and primary data can be collected from the recycling plant to get reliable results. The logistics involved in collection of used EEE equipment to the recycling system has to be modeled with proper inventory data to get reliable results. The cost involved in recycling must also be assessed to understand if it really makes sense to recycle these products. LCA results show that distance travelled in collecting the e-waste for recycling results in impacts like fossil fuels or respiratory inorganics (Barba-Gutiérrez et al., 2008). The recovery of secondary raw materials in the material recovery phase like that yittrium was studied and proved to be beneficial than the original production of yittrium (Rocchetti and Beolchini, 2014).

Mechanical recycling is reported to be more environmentally effective option when compared to energy recovery and incernation (Dodbiba et al., 2008). LCA of various EOL options of notebooks show that recycling of some components creates negative impacts than other alternatives, hence it is better to improve the commercial life cycle of the product using effective design rather than stressing on recycling and recovery (Deng et al., 2011). On the contrary material recycling of electronic scrap from mobile phone networks can reduce the environmental impact by 50% (Wolfram Scharnhorst et al., 2005). The *toxicological emission* in the EOL phase of ICT products is dominated by copper in the PCBs, also burning of cell phones to recover rare metals shows critical effects, all this indicates the requirement in design manufacturing phase to reduce the components with high toxic components being assembled in electronic products (Hibbert and Ogunseitan, 2014).

Environmental evaluation of WEEE done using LCA and multivariate statistical techniques makes it easy to benchmark a range of products and processes and also when the impact categories to be assessed is more, however this method can be used to evaluate other phases of a wide range of product categories (Barba-Gutiérrez et al., 2008). *Rechargeable batteries* are accounted for hazardous metal pollutants and release Co, Cu, Ni, and Pb under simulated landfill conditions (Kang et al., 2013); however lack of data in many phases of battery makes it difficult to conclude.

Plastics when treated in its EOL via recycling produces lesser impacts compared to incernation; however more complete modeling has to be carried out for other

WEEE fractions as well (Wager et al., 2011). Also LCA studies show that mechanical recycling of plastics is more attractive treatment option than incernations and hence plastic components like PVC in TVs must be reduced or avoided (Dodbiba et al., 2008). It is time and again proved that better product design, effective recycling options depending on WEEE fraction of the product, and wise recycler selection reduce environmental impacts (Zhang et al., 2004).

Recycling of *home appliances* proved to be an environmentally beneficial choice in Japan in reducing CO2 emission, depletion of abiotic resources, generation of waste, and landfill consumption, provided the rate of retrieval remains were maintained at a high level (Nakamuraa and Kondo, 2004). The process that uses acqua regia has better environmental performance in recovering Cu form *PCB scrap*, these kind of LCA analysis is very essential especially in countries where effective recycling options are not in place and electronic products are disposed of to landfill (Rubin et al., 2014). Also P-PCBs showed lesser environmental impacts compared to the O-PCBs (Liu et al., 2014).Environmental evaluation of ball grid array (BGA) and chip scale packaging (CSP) using screening LCA revealed that the shift in technology could be eco-efficient, however a full LCA was suggested by the authors with well-defined parameters to validate their findings (Andrae and Andersen, 2011).

Extension of life span of a product by reselling or upgrading is wiser option to reduce energy impacts (Williams, 2004). The potential benefits of increasing a products lifetime and its positive effects on impacts was evaluated using WM as a case study and simplified and a general indices were developed, however the authors concluded that though benefits are seen owing to the extension of lifetime of a product, it is variable due to factors like impact category, consumers behavior pattern in terms extending the life span impact of repair, and the efficiency of the replacement product (Ardente and Mathieux, 2014).

When ICT products produced within a gap of a decade were compared, it was found that the newly developed products showed a substantial decrease in greenhouse gas (GHG) emissions, the reason being the decrease in the ICs and PCBs, Linear regression model was used by the authors and was reported to be a best fit and recommended to be used in first order LCA and has a promising future when explored further (Teehan and Kandlikar, 2013). The authors identified a linear relationship between mass and the embodied carbon emissions (Teehan and Kandlikar, 2013).

CF of certain activities that were not previously assessed for ICT products like data transport networks and data centers and manufacturing of network infrastructure were modeled, the authors also suggested focus on end user equipment and use time is more relevant as the data volume used depends on the use time (Malmodin et al., 2014). E commerce is an option to overcome this effect but it again has its own implications. It is most favorable when air freight is not used consumer automobile services are altered by courier service (Norris et al., 2003). The hot spots identified in LCA studies were classified as controllable and uncontrollable options. Controllable are those that can be controlled by the company; uncontrollable are those that cannot be controlled by the company like usage pattern. An environmental scoring system was recommended for easy understanding of the product designers who are non-LCA practitioners (Seungdo Kim, 2001).

5.4. Comparative studies

Many studies dealt with comparing print versions and online versions of newspapers, movies, book reading, etc. It was also concluded that online media is more environmentally beneficial than conventional print media. In such comparison that involve many criteria, functional unit is very important, and at the same time it is arguable, so based on these assumptions giving wrong conclusions and research directions must be avoided. Also in these comparisons, inventory data for the life cycle phases of the computers involved, usage pattern and standby mode, electricity consumptions, internet usage and telephone networks have to be carefully modeled to get reliable results (Reichart and Hischier, 2002).

When digital libraries were compared with traditional format energy consumption was influenced by the number of readings per article, transportation involved in carrying the books, and photocopying. It was reported that laser printing produced lesser impacts compared to online reading and networking infrastructure resulted in lesser impacts (Gard and Keoleian, 2003).

Similarly when paper and e-invoicing were compared, e invoicing seemed better superficially, but that conclusion has to be further dug into considering factors like allocation, avoiding printing in e-voice, and how the e-voice system is designed and manufactured (Moberg et al., 2010).

Between the 3 competing technology of CRT and LCD and plasma, newer flat panel displays were reported to create less impacts compared to CRT technologies (Lim and Schoenung, 2010), plasma created less impacts compared to LCD. However the bottom line is all technologies reflected high impacts in production and use phase (which has to be verified) and EOL showing benefits (Hischier and Baudin, 2010). In the disposal phase LCD monitor showed lower impacts compared to CRT monitors except for the mercury management category.

6. Future trends

LCA in future has to be used as a tool to quantify the cumulative effect of group of electronic products on a community, region or country and comparisons can also be made for interesting results. Eco-design suggestions can be provided for a series of low-profile and less complex products based on LCA results, and for which primary data can be applied in use and EOL phase. Expansion of PCR libraries is also a welcome change. More countries can develop PCR libraries to avoid uncertainties in LCA like user profiles, logistics, electricity mix (Weber, 2012).

With reuse and recycling being emphasized so much nowadays, environmental benefits of products using virgin materials and recycled materials can be assessed and compared (Andreola, 2005). In countries where there is no recycling facility, the EOL management has to be studied especially in those countries to understand the effects and impacts of disposed electronic products. Further simplification of LCA for EOL phase has to be investigated and addressed in more detail for ICT products (Moberg et al., 2014). Metals, flame retardants and long terms effects of emissions from landfills have to be evaluated using LCIA especially for ICT products as these have many critical effects on human health and ecosystem quality (Wolfram Scharnhorst et al., 2005). Recycling and disposal practices in emerging economies have to be studied where electricity generation and cost involved might be different and these results will help make some useful change in WEEE directives (Mayers et al., 2005).

When evaluating CF, apart from the emission factors taken form the companies, information from suppliers, usage and disposal stage of electronic products will provide holistic results (Vasan et al., 2014). In future national emissions have to be considered like in the case of Luxemburg where the country's GHG emissions for its net consumption was evaluated over a period of time using hybrid LCA instead of an IPCC approach considering both consumer and producer perspectives (Caro et al., 2015). Such national-level assessments performed in emerging countries will provide results on impacts created, also instead of only GHG emissions effects on human health and ecosystem quality can be measured on the whole.

A new concept of *global change mix factor* (GCMF) introduced along with ALCA to present AALCA and sensitivity checks were first performed for the market changes. Notions like smart phones have replaced alarm clocks, digital cameras, and watches must be explored, more on implementation of CLCA, ALCA, and AALCA and how well they complement each other on a range of electronic products can be explored also usage of price units instead of physical units in GCMF can be investigated and cumulative effects of usage of smart phones for an extended period like 2020 will also produce some interesting results (Andrae, 2014). The EOL of CNT switches used in phone memory has to be evaluated for toxic emissions, modeling of nano-enabled products is still weak in this area (Dahlben et al., 2013). LCA studies related mobile phones show that UMTS proved to be better than GSM service (Faist Emmenegger et al., 2004); however now with 4 G in place, there is a lot of component and technology changes which has to be analyzed.

Within the category of ICT devices, desktops & notebooks have received major attention, but integrated desktop has not received any scholarly attention so far. In most of the houses to avoid the hassles of having CPU, an all in one unit is preferred; however this product has not been analyzed so far, for its environmental implications. Even a comparison between a conventional desktop PC and an integrated desktop will fetch some interesting results. Temporal trends in manufacturing phase of notebooks, energy use in operation phase have to be quantified more realistically (Deng et al., 2011). The potential of ICT sector, as a source to decrease the environmental impacts created by many other product categories can be modeled (Malmodin et al., 2010). ICT products have to be evaluated in future more accurately and studies can be compared based on spatial environmental balance (SEB) to understand how geography plays an important role in LCA results, since LCA weighs different phases of LCA based in different location (Daiyue et al., 2015).

Also hybrid LCA exhibits advantages over conventional LCA in terms of implementing a wide range of alternative scenarios with regard not only to the manufacturing phase, but also to the phase of use and end of life (Nakamuraa and Kondo, 2004). For company-level assessments in particular electronic industry with raw materials and production processes involving a huge supply chain, hybrid LCA is more practicable. Huge data sets in LCA can be handled using MDS techniques (Gutiérrez et al., 2009).

Many authors have time and again stated the importance of setting up appropriate system boundaries, and at the same time how difficult it is to create one, Rafael Laurenti et al (Laurenti et al., 2014) stated that GMB (group model building) and CLD can serve this purpose. The authors demonstrated this for WM, similar procedure can be followed for other products especially complex ICT products. The commonly used functional units, life cycle stages and system boundaries can be determined based on literature review and variables that are left out from the analysis but may influence the LCA results can be evaluated using cause effect links and feedback loops (Laurenti et al., 2014). These approaches would bridge the gap between quantitative and qualitative variables, improve the conclusion & recommendations given by LCA studies (Laurenti et al., 2014).

When comparisons are made between ICT products and traditional counterparts more in depth analysis has to be carried out with methodological guidelines considering indirect and rebound effect for realistic results (Mirabella et al., 2013). There is not always a single answer as to which one is better in these kind of comparisons, obvious choices like switching off the devices when not in use, prolonging the lifetime of the device as much as possible, dispose of in a proper way and use material recovery and recycling as EOL option are all options to mitigate impacts; however in the future, toxicological emissions have to be evaluated. Only when inventories are developed more impact categories can be created and analyzed especially for complex electronic products (Moberg et al., 2010).

In the domain of electronic media, some issues in performing LCA include the data collection strategy, desktop search and dismantling and the influence of geographical location on parameters like electricity mix, recycling options play a significant effect on results (Hischier et al., 2014). In future assumptions on these grounds can be checked with spatial sensitivity analysis, also LCI models with different data collection approaches can be tested for interesting results (Hischier et al., 2014). When comparing display technologies in TVs, environmental benefits of recent technologies is reflected, however relevance of inclusion of nano particles releases into LCA studies is essential for more reliable evaluation (Hischier, 2015).

In general we assume that rechargeable batteries create lesser impacts, however the usage phase and EOL phase are very crucial in confirming this notion, usage pattern of rechargeable batteries and their disposal state also has to be modeled to verify this assumption (Lankey and McMichael, 2000). FTM (Factory through Mall) phase is ignored or conveniently assumed to create least significant impacts, which might not be the case necessary and was tested by Norris et al. (2001). In future this phase has to be modeled carefully to fetch accurate overall results. Impact category DLU is not given as much importance as CED or GWP or any other impact (Sibylle D. Frey, 2006). This category when studied might fetch interesting results.

7. Gaps identified

Two of the major challenges faced by LCA tool are the data acquisition and its applicability in industrial practices for decision-making. Our literature analysis clearly indicates that LCA has been used primarily by academia, more so in developed countries. As a technology improves and matures over a period of time more attention has to be paid to its effective utilization in business and organizations to serve the public and society in a larger sense. Moreover more opportunities must be provided for LCA practitioners worldwide within academia and industries to design, develop, implement and evaluate LCA for electronic products. Despite the opportunities existing currently in this area, there is still a long way to go for extensive global application of LCA for electronic products.

There are still many challenges to overcome and problems to be solved to enable widespread implementation of LCA as a DMT within electronics industry globally. Broadly the drawbacks or limitation of using LCA as a DMT can be classified into (1) boundary scoping, (2) methodologies used, (3) data collection procedures and finally (4) industrial practices. One more important point of consideration is the ultimate end result of using LCA as DMT. A good number of case studies analyzed in this review indicate the effective use of LCA in environment impact assessment and hot spot identification. But did these results play any role in reducing the environmental impacts of the corresponding products to the fullest? Has it been further verified? Hence going forward LCA has to be used as a DMT in order to improve the environmental impacts throughout the product's life cycle.

As outlined above, for LCA to effectively work, it is absolutely essential to solve the two major challenges it is currently facing, namely data availability and the limitations related to its usage as a DMT. The limitations of using LCA within decision-making has also been highlighted above. In this context, following are some important gaps identified from this literature analysis that merit future attention:

7.1. Practices

Difficulties are being encountered in conducting LCA studies for large group of products, region, sector etc. It is understood that it is more complicated to conduct such assessments than for a single conventional electronic product, as there are more data requirements, each product is unique and has multiple functions to assess. However, more research on LCA being used to quantify the net environmental impacts created by a group of electronic products within a sector, country, and region is essential (Ryen et al., 2015). Comparison within different countries will also fetch interesting results. Country-level assessments are more crucial than product-level assessments to understand consumption of resources and usage behavior at macrolevel. Eco-design suggestions on products for reducing the cumulative energy usage and emissions can also be given on a larger scale based the geographical limitation of that region.

Focus on low-profile electronic products and some products within ICT devices like integrated desktops, kindle, intermediate processes and products, internet service providers and data centers are needed in future LCA studies. Studies focusing on checking the validity of Eco-labeled products will also pave way for effective usage of LCA within industrial practices.

7.2. Data inventories

Future research has to use actual industry data instead of relying on subjective opinions. More LCA studies using primary data to model the use and EOL phase of electronic products will continue developing this field of research (Gutiérrez et al., 2009). Even in cases where mix of data types are used, data quality indicators (measured, calculated, estimated, and not reported) have to be included for transparency in the kind of data used, which will enable decision-making.

7.3. Methodology framework

Carbon footprint analysis of electronic products should include emission factors from not only companies, also from suppliers, use and disposal of products (Vasan et al., 2014). Impacts created by the ICT devices on PCF can be evaluated on large scale to understand the cumulative effects over a time frame for a specific region or country (Caro et al., 2015). Focusing on analyzing the most significant sources of NF_3 emissions and its possible effect on GWP also needs attention (Thomas et al., 2011). Energy and Carbon are the most evaluated impact categories especially when it comes to ICT products. In future, land areas consumed by the raw and mined materials must be considered more for CEP (Sibylle D. Frey, 2006). Steps in the manufacturing process have to be included more in detail. Nanomaterial evaluation has to be included in LCA studies of ICT products for better results (Hischier, 2014). Temporal uncertainty and life span uncertainty have to be addressed and justified (Weber, 2012). More LCA types must be explored and compared with the help of case studies of various products to provide comprehensive results (Nakamuraa and Kondo, 2004).

More models and conceptual frameworks must be developed combining different approaches and methods. Such integrated models with LCA as a DMT using

TBL (Triple bottom line approach) approach will eventually pave the way toward sustainability. Product Sustainability Index, Ecological and Social Material Index/ Indicators for EOL of electronic products, and Web-based system for individual electronic products indicating an overall environmental score are some areas to explore; however all these require a well-planned research agenda to achieve desirable results (Herrmann et al., 2004).

7.4. Boundary scoping

Appropriate system boundaries, life span of the products under consideration, clear reporting of results in terms of the: (1) LCIA methods used, (2) most relevant impact category, and (3) life cycle phase that needs attention are very essential (Laurenti et al., 2014). Few life cycle phases that involve geographical factor like electricity mix and recycling systems prevailing have to be more carefully evaluated using SEB (Daiyue et al., 2015), (Hischier et al., 2014). EOL management options especially in countries where recycling facilities are not available and electronic products are landfilled must be studied to model the damage created (Barba-Gutiérrez et al., 2008), (Mayers et al., 2005), (Wolfram Scharnhorst et al., 2005).

7.5. Notions

General beliefs like rechargeable batteries are superior to conventional ones, online media is better that print media, and mobile phones have replaced watch and cameras, ignoring the distribution phase especially the FTM phase precisely in most models, recycling as a viable option in EOL management and finally cornering use phase as the most dominant phase in energy using ICT devices, have to be revisited and checked for validity (Andrae, 2014; Norris et al., 2003).

We hope that the future work on LCA within electronics industry will bridge the gap between theoretical frameworks developed and the normal business practices followed and enable decision-making in the process by developing reliable models and frameworks using quality data. Also we hope that in the future, reporting of results in LCA studies meet the industry needs and is presented in such a way that it can be understood even by non-LCA practitioners. This will eventually help in LCA not getting categorized as a data starved, sophisticated, and complex tool that needs an expert support when employed for decision-making.

8. Conclusions

This paper reports on a comprehensive literature review of LCA and consumer electronic products summarizing the developments made so far and indicating future trends. This area of research has seen rapid growth in the last decade. We conducted a narrative review from which it is clearly evident that ICT products have received more scholarly attention compared to other electronic products. We carried out a systematic review using two classification frameworks to identify research trends and knowledge gaps in this field. In general, most of the studies concluded that use phase, EOL phase, and production phase are the most dominant ones in creating negative environmental impacts in that order. However some discrepancies between the studies and some limitations for using LCA as an effective DMT have been found in the literature. Literature shows evidence that the environmental variant of the LCA has been widely used for decision-making whereas the social and economic dimension are still not included, or even if included all three dimensions of sustainability are not integrated in one model. Also from the literature, it is quite clearly evident that lack of data inventory, inhibitions from the business communities, or industry to reveal data makes it more difficult to conduct LCA of energy using consumer electronic products and aid decision-making. Finally, this work also presented available literature gaps, as a result of critical review on various life cycle studies conducted on consumer electronic products, for further studies to focus on.

Clearly there are limitations in this work. First when the usage of keywords was expanded, we might have got more relevant papers in this area of research. Second the decision of including the 134 papers in this review was subjective, decided by the sole discretion of the authors only. The literature collection was carried out using only one database SCOPUS. However with all these stated limitations, we believe our review work is very comprehensive in presenting the current trends and future research recommendations in this research area. This review can be further extended by reviewing and comparing individual LCA results of each product category to understand their relative impacts. This can be done on a country level or regional level as well.

In view of the rapid development of electronic industry numerous regulations have been passed by EU. With customers also opting for eco-friendly products, governments and industries have also started investing on research & development of environmental friendly products. At this point, LCA plays a crucial role as it is one of the widely established system-analysis tools to evaluate the complete life cycle of a product. Conducting LCA to understand how a consumer electronic product hurts or helps nature is the future; therefore, it would be interesting to see how countries who have not taken sustainability initiatives so far will adapt to this changing trend. It is also very important for business people to understand LCA and incorporate life cycle thinking into their product in the design stage itself, because in the future such labels will even add value to the brand image of the products. Similarly with manufacturers and industry people being involved in sustainable measures, it is essential for the LCA practitioners and researchers to make sure that future research directions in this area are useful in enabling decision-making, reliable and understandable for further implementation. It is hoped that this comprehensive review provides some useful insights to the readers in terms of understanding the current trends in LCA of electronic products, identify knowledge gaps, and provide future research recommendations.

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References

Achachlouei, M. A., and Moberg, Å. (2015). Life cycle assessment of a magazine, part II: A comparison of print and tablet editions. *J. Ind. Ecol.*, n/a–n/a. doi:10.1111/jiec.12229

Alessandra papetti, M. G., and Mandolini, Marco (2014). Product innovations and eco-sustainability: An approach to evaluate the relationships. *Key Eng. Mater.*, 572, 74–77.

Alston, S. M., and Arnold, J. C. (2011). Environmental impact of pyrolysis of mixed WEEE plastics part 2: Life cycle assessment. *Environ. Sci. Technol.*, 45(21), 9386–9392. doi:10.1021/es2016654

Anders, S.G., Andræ, P. M., Anderson, Johan and Liu, Johan (2004). Uncertainty estimation by Monte Carlo simulation applied to life cycle inventory of cordless phones and microscale metallization processes. *IEEE Trans. Electron. Packag. Manuf.*, 27(4), 233–245.

Andre, Anders S.G., Östermark, U., and Liu, J. (2000). Life-cycle-assessment-of-a-telecommunications-exchange. *J. Electron. Manuf.*, 10(3), 147–160.

Andrae, A.S.G. (2014). Method based on market changes for improvement of comparative attributional life cycle assessments. *Int. J. Life Cycle Assess.*, 20(2), 263–275. doi:10.1007/s11367-014-0830-2

Andrae, A.S.G., and Andersen, O. (2010). Life cycle assessments of consumer electronics—Are they consistent? *Int. J. Life Cycle Assess.*, 15(8), 827–836. doi:10.1007/s11367-010-0206-1

Andrae, A.S.G., and Andersen, O. (2011). Life cycle assessment of integrated circuit packaging technologies. *Int. J. Life Cycle Assess.*, 16(3), 258–267. doi:10.1007/s11367-011-0260-3

Andræ, A.S.G., Andersson, D. R., and Liu, J. (2005). Significance of intermediate production processes in life cycle assessment of electronic products assessed using a generic compact model. *J. Cleaner Prod.*, 13(13-14), 1269–1279. doi:10.1016/j.jclepro.2005.05.013

Andrae, A.S.G., Itsubo, N., and Inaba, A. (2007). Global environmental impact assessment of the Pb−free shift. *Soldering Surf. Mount Technol.*, 19(2), 18–28. doi:10.1108/09540910710836502

Andrae, A.S.G., Zou, G., and Liu, J. (2004). LCA of electronic products: An environmental assessment of gallium arsenide monolithic microwave integrated circuit system-in-a-package (SIP) switch product. *Int. J. Life Cycle Assess.*, *9*(1), 45–52.

Andreola, F. (2005). Cathode ray tube glass recycling: An example of clean technology. *Waste Manage. Res.*, 23(4), 314–321. doi:10.1177/0734242×05054422

Andreola, F., Barbieri, L., Corradi, A., Ferrari, A. M., Lancellotti, I., and Neri, P. (2006). Recycling of EOL CRT glass into ceramic glaze formulations and its environmental impact by LCA approach. *Int. J. Life Cycle Assess.*, 12(6), 448–454. doi:10.1065/lca2006.12.289

Ardente, F., and Mathieux, F. (2014). Environmental assessment of the durability of energy-using products: Method and application. *J. Cleaner Prod.*, 74, 62–73. doi:10.1016/j.jclepro.2014.03.049

Arushanyan, Y., Ekener-Petersen, E., and Finnveden, G. (2014). Lessons learned—Review of LCAs for ICT products and services. *Comput. Ind.*, 65(2), 211–234. doi:10.1016/j.compind.2013.10.003

Barba-Gutiérrez, Y., Adenso-Díaz, B., and Hopp, M. (2008). An analysis of some environmental consequences of European electrical and electronic waste regulation. *Resour. Conserv. Recycl.*, 52(3), 481–495. doi:10.1016/j.resconrec.2007.06.002

Barba-Gutiérrez, Y., Adenso-Díaz, B., and Lozano, S. (2008). Eco-efficiency of electric and electronic appliances: A data envelopment analysis (DEA). *Environ. Model. Assess.*, 14(4), 439–447. doi:10.1007/s10666-007-9134-2

Biganzoli, L., Falbo, A., Forte, F., Grosso, M., and Rigamonti, L. (2015). Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy). *Sci. Total Environ.*, 524–525, 361–375. doi:10.1016/j.scitotenv.2015.04.041

Bigum, M., Brogaard, L., and Christensen, T. H. (2012). Metal recovery from high-grade WEEE: A life cycle assessment. *J. Hazard. Mater.*, 207–208, 8–14. doi:10.1016/j.jhazmat.2011.10.001

Borggren, C., Moberg, Å., and Finnveden, G. (2011). Books from an environmental perspective—Part 1: Environmental impacts of paper books sold in traditional and internet bookshops. *Int. J. Life Cycle Assess.*, 16(2), 138–147. doi:10.1007/s11367-011-0254-1

Bull, J. G., and Kozak, R. A. (2014). Comparative life cycle assessments: The case of paper and digital media. *Environ. Impact Assess. Rev.*, 45, 10–18. doi:10.1016/j.eiar.2013.10.001

Caro, D., Rugani, B., Pulselli, F. M., and Benetto, E. (2015). Implications of a consumer-based perspective for the estimation of GHG emissions. The illustrative case of Luxembourg. *Sci. Total Environ.*, 508, 67–75. doi:10.1016/j.scitotenv.2014.11.053

Choi, B.-C., Shin, H.-S., Lee, S.-Y., and Hur, T. (2004). Life cycle assessment of a personal computer and its effective recycling rate (7 pp). *Int. J. Life Cycle Assess.*, 11(2), 122–128. doi:10.1065/lca2004.12.196

Christopher Ciantar, M. H. (2000). An environmental evaluation of mechanical systems using environmentally acceptable refrigerants. *Int. J. LCA*, 5(4), 209–220. doi:10.1065/Ica2000.04.024

Cullen, J. M., and Allwood, J. M. (2009). The role of washing machines in life cycle assessment studies. *J. Ind. Ecol.*, 13(1), 27–37. doi:10.1111/j.1530-9290.2009.00107.x

Dahlben, L. J., Eckelman, M. J., Hakimian, A., Somu, S., and Isaacs, J. A. (2013). Environmental life cycle assessment of a carbon nanotube-enabled semiconductor device. *Environ. Sci. Technol.*, 47(15), 8471–8478. doi:10.1021/es305325y

Daiyue, H., Chao, L., and Puel, G. (2015). Spatial environmental balance to information and communication technology products in different regions of China by using LCA. *J. Cleaner Prod.*, 91, 128–135. doi:10.1016/j.jclepro.2014.11.025

Deng, L., Babbitt, C. W., and Williams, E. D. (2011). Economic-balance hybrid LCA extended with uncertainty analysis: Case study of a laptop computer. *J. Cleaner Prod.*, 19(11), 1198–1206. doi:10.1016/j.jclepro.2011.03.004

Dobon, A., Cordero, P., Kreft, F., Østergaard, S. R., Antvorskov, H., Robertsson, M., Smolander, M., and Hortal, M. (2011). The sustainability of communicative packaging concepts in the food supply chain. A case study: Part 2. Life cycle costing and sustainability assessment. *Int. J. Life Cycle Assess.*, 16(6), 537–547. doi:10.1007/s11367-011-0291-9

Dodbiba, G., Takahashi, K., Sadaki, J., and Fujita, T. (2008). The recycling of plastic wastes from discarded TV sets: Comparing energy recovery with mechanical recycling in the context of life cycle assessment. *J. Cleaner Prod.*, 16(4), 458–470. doi:10.1016/j.jclepro.2006.08.029

Duan, H., Eugster, M., Hischier, R., Streicher-Porte, M., and Li, J. (2009). Life cycle assessment study of a Chinese desktop personal computer. *Sci. Total Environ.*, 407(5), 1755–1764. doi:10.1016/j.scitotenv.2008.10.063

Dodbiba, G., Furuyama, T., Takahashi, K., Sadaki, J., and Fujita, T. (2007). Life cycle assessment—A tool for evaluating and comparing different treatment options for plastic wastes from old television sets. *Data Sci. J.*, 6(6), S39–S50.

Ekvall, T., and Andrae, A. (2005). Attributional and consequential environmental Assessment of the shift to lead-free solders (10 pp.). *Int. J. Life Cycle Assess.*, 11(5), 344–353. doi:10.1065/lca2005.05.208

Elduque, D., Javierre, C., Pina, C., Martínez, E., and Jiménez, E. (2014). Life cycle assessment of a domestic induction hob: Electronic boards. *J. Cleaner Prod.*, 76, 74–84. doi:10.1016/j.jclepro.2014.04.009

Eun, J.-H., Son, J.-H., Moon, J.-M., and Chung, J.-S. (2009). Integration of life cycle assessment in the environmental information system. *Int. J. Life Cycle Assess.*, 14(4), 364–373. doi:10.1007/s11367-009-0076-6

Faist Emmenegger, M., Frischknecht, R., Stutz, M., Guggisberg, M., Witschi, R., and Otto, T. (2004). Life cycle assessment of the mobile communication system UMTS: Towards eco-efficient systems (12 pp). *Int. J. Life Cycle Assess.*, 11(4), 265–276. doi:10.1065/lca2004.12.193

Feng, C., and Ma, X. Q. (2009). The energy consumption and environmental impacts of a color TV set in China. *J. Cleaner Prod.*, 17(1), 13–25. doi:10.1016/j.jclepro.2008.03.007

Finnveden, Å.M.C.B.G. (2011). Books from an environmental perspective—Part 2 e-books as an alternative to paper books. *Int. J. Life Cycle Assess.*, 16, 238–246.

Gamberini, R., Gebennini, E., Manzini, R., and Ziveri, A. (2010). On the integration of planning and environmental impact assessment for a WEEE transportation network—A case study. *Resour. Conserv. Recycl.*, 54(11), 937–951. doi:10.1016/j.resconrec.2010.02.001

Gard, D. L., and Keoleian, G. A., (2003). Digital versus print energy performance in the selection and use of scholarly journals. *J. Ind. Ecol.*, 6(2), 115–132.

Gay, R. H., Davis, R. A., Phillips, D. T., and Sui, D. Z. (2005). Modeling paradigm for the environmental impacts of the digital economy. *J. Organ. Comput. Electron. Commerce*, 15(1), 61–82. doi:10.1207/s15327744joce1501_4

Gheewala, S., and Nielsen, P. (2003). Central and individual air-conditioning systems—A comparison of environmental impacts and resource consumption in a life cycle perspective. *Int. J. Sustainable Dev. World Ecol.*, 10(2), 149–155. doi:10.1080/13504500309469793

Graedel, T. E. (1997). Designing the ideal green product LCA SCLA in reverse. *Int. J. LCA*, *2*(1), 25–31.

Grignon-Massé, L., Rivière, P., and Adnot, J. (2011). Strategies for reducing the environmental impacts of room air conditioners in Europe. *Energy Policy*, 39(4), 2152–2164. doi:10.1016/j.enpol.2011.02.004

Gutiérrez, E., Lozano, S., and Adenso-Díaz, B. (2010). Dimensionality reduction and visualization of the environmental impacts of domestic appliances. *J. Ind. Ecol.*, 14(6), 878–889. doi:10.1111/j.1530-9290.2010.00291.x

Gutiérrez, E., Adenso-Diaz, B., Lozano, S., and Barba-Gutiérrez, Y. (2009). Visualisation of LCA environmental impacts of electrical and electronic products using multidimensional scaling. *Int. J. Prod. Lifecycle Manage.*, *4*(1/2/3), 166–185.

Hans de Bruijn, Hans, van Duin, Robert, Huijbrechts, Mark and Heijungs, Reinout (2002). *Handbook on life cycle assessment-operational guide to the ISO standards* Series editor: Jeroen B. Guinée, (Vol. 7). Kluwer Academic Publishers, New York, Boston, Dordrecht, London, Moscow.

Herrmann, C., Eyerer, P., and Gediga, J. (2004). Economic and ecological material index for end-of-life and design of electronic products. *IEEE Trans. Electron. Packag. Manuf.*, 27(1), 2–8.

Hibbert, K., and Ogunseitan, O. A. (2014). Risks of toxic ash from artisanal mining of discarded cellphones. *J. Hazard. Mater*, 278, 1–7. doi:10.1016/j.jhazmat.2014.05.089

Hischier, I., and Hischier, R. (2003). The environmental impact of getting the news: A comparison of on line, television, and newspaper information delivery. *J. Ind. Ecol.*, 6(3-4), 185–200.

Hischier, R. (2014). Life cycle assessment study of a field emission display television device. *Int. J. Life Cycle Assess.*, 20(1), 61–73. doi:10.1007/s11367-014-0806-2

Hischier, R. (2015). Grey energy and environmental impacts of ICT hardware. *Adv. Intell. Syst. Comput.*, 310, 171–189.

Hischier, R., Achachlouei, M. A., and Hilty, L. M. (2014). Evaluating the sustainability of electronic media: Strategies for life cycle inventory data collection and their implications for LCA results. *Environ. Model. Software*, 56, 27–36. doi:10.1016/j.envsoft.2014.01.001

Hischier, R., and Baudin, I. (2010). LCA study of a plasma television device. *Int. J. Life Cycle Assess.*, 15(5), 428–438. doi:10.1007/s11367-010-0169-2

Hishier, R. (2015). The transition from desktop computers to tablets. *Adv. Intell. Syst. Comput.*, 310, 243–256.

Hochschorner, E., Dán, G., and Moberg, Å. (2015). Carbon footprint of movie distribution via the internet: A Swedish case study. *J. Cleaner Prod.*, 87, 197–207. doi:10.1016/j.jclepro.2014.09.012

Hossain, M. S., Marwah, M., Shah, A., Watson, L. T., and Ramakrishnan, N. (2014). AutoLCA. *ACM Trans. Intell. Syst. Technol.*, 5(2), 1–21. doi:10.1145/2505270

Hur, T., Lee, J., Ryu, J., and Kwon, E. (2005). Simplified LCA and matrix methods in identifying the environmental aspects of a product system. *J. Environ. Manage.*, 75(3), 229–237. doi:10.1016/j.jenvman.2004.11.014

Huulgaard, R. D., Dalgaard, R., and Merciai, S. (2013). Ecodesign requirements for televisions—Is energy consumption in the use phase the only relevant requirement? *Int. J. Life Cycle Assess.*, 18(5), 1098–1105. doi:10.1007/s11367-013-0554-8

Iakovou, E., Moussiopoulos, N., Xanthopoulos, A., Achillas, C., Michailidis, N., Chatzipanagioti, M., Koroneosb, C., Bouzakis. K.-D., and Kikis, V. (2009). A methodological framework for end-of-life management of electronic products. *Resour. Conserv. Recycl.*, 53(6), 329–339. doi:10.1016/j.resconrec.2009.02.001

ISO (2006a). ISO 14040 International Standard. In: *Envirnometal management-life cycle assessment—Principles and framework*. International Organisation for Standardisation: Geneva, Switzerland. http://www.iso.org/iso/catalogue_detail?csnumber=37456

Huisman, Jaco, Stevels, A.L.N., and Stobbe, I. (2002). Eco-efficiency considerations on the end-of-life of consumer electronic products. *IEEE*, 59–64.

Junnila, S. (2008). Life cycle management of energy-consuming products in companies using IO-LCA. *Int. J. Life Cycle Assess.*, 13(5), 432–439. doi:10.1007/s11367-008-0015-y

Kang, D. H., Chen, M., and Ogunseitan, O. A. (2013). Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environ. Sci. Technol.*, 47(10), 5495–5503. doi:10.1021/es400614y

Lankey, R. L., and McMichael, F. C. (2000). Life-cycle-methods-for-comparing-primary-and-rechargeable-batteries. *Environ. Sci. Technol.*, 34, 2299–2304.

Laurenti, R., Lazarevic, D., Poulikidou, S., Montrucchio, V., Bistagnino, L., and Frostell, B. (2014). Group model-building to identify potential sources of environmental impacts outside the scope of LCA studies. *J. Cleaner Prod.*, 72, 96–109. doi:10.1016/j.jclepro.2014.03.001

Lee, K. M., and Park, P. (2001). Application of life-cycle assessment to type III environmental declarations. *Environ. Manage.*, 28(4), 533–546. doi:10.1007/s002670010242

Lim, S. R., and Schoenung, J. M. (2010). Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays. *J. Hazard. Mater.*, 177(1-3), 251–259. doi:10.1016/j.jhazmat.2009.12.025

Liu, J., Yang, C., Wu, H., Lin, Z., Zhang, Z., Wang, R., Li, B., Kang, F., Shi, L., and Wong, C. P. (2014). Future paper-based printed circuit boards for green electronics: Fabrication and life cycle assessment. *Energy Environ. Sci.*, 7(11), 3674–3682. doi:10.1039/c4ee01995d

Lu, L.-T., Wernick, I. K., Hsiao, T.-Y., Yu, Y.-H., Yang, Y.-M., and Ma, H.-W. (2006). Balancing the life cycle impacts of notebook computers: Taiwan's experience. *Resour. Conserv. Recycl.*, 48(1), 13–25. doi:10.1016/j.resconrec.2005.12.010

Maga, D., Hiebel, M., and Knermann, C. (2012). Comparison of two ICT solutions: Desktop PC versus thin client computing. *Int. J. Life Cycle Assess.*, 18(4), 861–871. doi:10.1007/s11367-012-0499-3

Malmodin, J., Lundén, D., Moberg, Å., Andersson, G., and Nilsson, M. (2014). Life cycle assessment of ICT. *J. Ind. Ecol.*, 18(6), 829–845. doi:10.1111/jiec.12145

Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., and Lövehagen, N. (2010). Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors. *J. Ind. Ecol.*, 14(5), 770–790. doi:10.1111/j.1530-9290.2010.00278.x

Margaret Simonson, C., Hakan Stripple, T. (2002). Fire-LCA study of TV sets with V0 and HB enclosure material. *Chemosphere*, 46, 737–744.

Maria Leet Socolof, M.B.S., Kincaid, Lori E., Overly, Jonathan G., Hart, Katherine M. and Singh, Dipti (1999). Environmental life-cycle design tool for assessing impacts of CRT and LCD monitors. *IEEE*, 232–237.

Marissa Yao, T. H., Cullen, Micheal J., stewert, Scott and Brady, Todda (2010). Comparative assessment of life-cycle assessment methods used for personal computers. *Environ. Sci. Technol.*, 44, 7335–7346.

Masafumi Tekawa, S. M., and Inaba, Atsushi (1997). Life cycle assessment: An approach to environmentally friendly PCs. *IEEE*, 125–130.

Mayers, C. K., France, C. M. and Cowell, S. J. (2005). Extended producer responsibility for waste electronics an example of printer recycling in the United Kingdom. *J. Ind. Ecol.*, *9*(3), 169–189.

Menikpura, S.N.M., Santo, A., and Hotta, Y. (2014). Assessing the climate co-benefits from waste electrical and electronic equipment (WEEE) recycling in Japan. *J. Cleaner Prod.*, 74, 183–190. doi:10.1016/j.jclepro.2014.03.040

Miller, I., Shelly, M., Jonmaire, P., Lee, R. V., and Harbison, R. D. (2005). Assessing contributory risk using economic input-output life-cycle analysis. *Int. J. Environ. Health Res.*, 15(2), 107–115. doi:10.1080/09603120500061625

Mirabella, N., Rigamonti, L., and Scalbi, S. (2013). Life cycle assessment of information and communication technology application: A case study of dematerialization in the Italian Public Administration. *J. Cleaner Prod.*, 44, 115–122. doi:10.1016/j.jclepro.2012.10.051

Moberg, Å., Borggren, C., Ambell, C., Finnveden, G., Guldbrandsson, F., Bondesson, A., Malmodin, J., and Bergmark, P. (2014). Simplifying a life cycle assessment of a mobile phone. *Int. J. Life Cycle Assess.*, 19(5), 979–993. doi:10.1007/s11367-014-0721-6

Moberg, A., Borggren, C., Finnveden, G., and Tyskeng, T. (2010). Environmental impacts of electronic invoicing. *Prog. Ind. Ecol.*, *7*(2), 93–113.

Moberg, Å., Johansson, M., Finnveden, G., and Jonsson, A. (2010). Printed and tablet e-paper newspaper from an environmental perspective—A screening life cycle assessment. *Environ. Impact Assess. Rev.*, 30(3), 177–191. doi:10.1016/j.eiar.2009.07.001

Monfared, B., Furberg, R., and Palm, B. (2014). Magnetic vs. vapor-compression household refrigerators: A preliminary comparative life cycle assessment. *Int. J. Refrig.*, 42, 69–76. doi:10.1016/j.ijrefrig.2014.02.013

Moraes, D.d.G.e.S.V.M., Rocha, T. B., and Ewald, M. R. (2014). Life cycle assessment of cell phones in Brazil based on two reverse logistics scenarios. *Produção*(ahead), 0–0. doi:10.1590/s0103-65132014005000011

Muñoz, I., Gazulla, C., Bala, A., Puig, R., and Fullana, P. (2008). LCA and ecodesign in the toy industry: Case study of a teddy bear incorporating electric and electronic components. *Int. J. Life Cycle Assess.*, 14(1), 64–72. doi:10.1007/s11367-008-0044-6

Nakamuraa, S., and Kondo, Y. (2004). Evaluating alternative life cycle strategies for electrical appliances by the waste input-output model. *Int. J. LCA*, 9(4), 236–246. doi:10.1065/Ica2004.03.153

Nakano, K., Aoki, R., Yagita, H., and Narita, N. (2006). Evaluating the reduction in green house gas emissions achieved by the implementation of the household appliance recycling in Japan. *Int. J. Life Cycle Assess.*, 12(5), 289–298. doi:10.1065/lca2006.11.281

Neuman, W. L. (2000). *Social research methods: Qualitative and quantitative approaches*, 4th edn. Boston: Allyn and Bacon.

Ngai, E.W.T., Moon, K.K.L., Riggins, F. J., and Yi, C. Y. (2008). RFID research: An academic literature review (1995–2005) and future research directions. *Int. J. Prod. Econ.*, 112(2), 510–520. doi:10.1016/j.ijpe.2007.05.004

Niu, R., Wang, Z., Song, Q., and Li, J. (2012). LCA of scrap CRT display at various scenarios of treatment. *Proc. Environ. Sci.*, 16, 576–584. doi:10.1016/j.proenv.2012.10.079

Noon, M. S., Lee, S.-J., and Cooper, J. S. (2011). A life cycle assessment of end-of-life computer monitor management in the Seattle metropolitan region. *Resour. Conserv. Recycl.*, 57, 22–29. doi:10.1016/j.resconrec.2011.09.017

Norris, G. A., Croce, F. D., and Jolliet, O. (2003). Energy-burdens-of-conventional-wholesale-and-retail-portions-of-product-life-cycles. *J. Ind. Ecol.*, 6(2), 59–69.

Park, P.-J., Lee, K.-M., and Wimmer, W. (2005). Development of an environmental assessment method for consumer electronics by combining top-down and bottom-up approaches (11 pp). *Int. J. Life Cycle Assess.*, 11(4), 254–264. doi:10.1065/lca2005.05.205

Park, P.-J., Tahara, K., Jeong, I.-T., and Lee, K.-M. (2006). Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine. *Resour. Conserv. Recycl.*, 48(1), 71–85. doi:10.1016/j.resconrec.2006.01.001

Park, P. J., Tahara, K., and Inaba, A. (2007). Product quality-based eco-efficiency applied to digital cameras. *J. Environ. Manage.*, 83(2), 158–170. doi:10.1016/j.jenvman.2006.02.006

Parsons, D. (2006). The environmental impact of disposable versus re-chargeable batteries for consumer use. *Int. J. Life Cycle Assess.*, 12(3), 197–203. doi:10.1065/lca2006.08.270

Pascal De Langhe, S. C., and Ceuterick, Dirk (1998). Green design of telecom products—The ADSL high speed modem as a case study. *IEEE Trans. Compon. Packag. Manuf. Technol.*, 21 (1), 154–167.

Reichart, I., and Hischier, R. (2002). The environmental impact of getting the news: A comparison of on-line, television, and newspaper information delivery. *Journal of Industrial Ecology*, 6(3–4), 184–200.

Rhodes, S. P. (1993). *Applications of life cycle assessment in the electronics industry for product design and marketing claims*. Paper presented at the IEEE International Symposium, Arlington, VA.

Rocchetti, L., and Beolchini, F. (2014). Environmental burdens in the management of end-of-life cathode ray tubes. *Waste Manage*, 34(2), 468–474. doi:10.1016/j.wasman.2013.10.031

Rubin, R. S., Castro, M.A.S.d., Brandão, D., Schalch, V., and Ometto, A. R. (2014). Utilization of life cycle assessment methodology to compare two strategies for recovery of copper from printed circuit board scrap. *J. Cleaner Prod.*, 64, 297–305. doi:10.1016/j.jclepro.2013.07.051

Ryen, E. G., Babbitt, C. W., and Williams, E. (2015). Consumption-weighted life cycle assessment of a consumer electronic product community. *Environ. Sci. Technol.*, 49(4), 2549–2559. doi:10.1021/es505121p

Sarah Boyd, A. H., and Dornfeld, David (2011). Life-cycle assessment of NAND flash memory. *IEEE Trans. Semicond. Manuf.*, 20(1), 117–124.

Satoshi Oikawa, K. E., and Fuse, Kensuke (2005). Fujitsu's approach for eco-efficiency factor. *J. Ind. Ecol.*, 41(2), 236–241.

Scharnhorst, W. (2006). Life cycle assessment in the telecommunication industry: A review. *Int. J. Life Cycle Assess.*, 13(1), 75–86. doi:10.1065/lca2006.11.285

Scharnhorst, W., Althaus, H.-J., Classen, M., Jolliet, O., and Hilty, L. M. (2005). The end-of-life treatment of second generation mobile phone networks: Strategies to reduce the environmental impact. *Environ. Impact Assess. Rev.*, 25(5), 540–566. doi:10.1016/j.eiar.2005.04.005

Scharnhorst, W., Hilty, L. M., and Jolliet, O. (2006). Life cycle assessment of second generation (2G) and third generation (3G) mobile phone networks. *Environ Int*, 32(5), 656–675. doi:10.1016/j.envint.2006.03.001

Schien, D., Shabajee, P., Yearworth, M., and Preist, C. (2013). Modeling and assessing variability in energy consumption during the use stage of online multimedia services. *J. Ind. Ecol.*, 17(6), 800–813. doi:10.1111/jiec.12065

Schneider, F., Salhofer, S., Schiffleitner, A., and Stachura, M. (2008). The development of an eco design product-eco mouse case study. *Prog. Ind. Ecol.*, *5*(1-2), 102–123.

Scott Matthewsa, H., Takashi Tagamic, E. W., and Hendricksond, C. T. (2002). Energy implications of online book retailing in the United States and Japan. *Environ. Impact Assess. Rev.*, 22, 493–507.

Kim, Seungdo, Hwang, Taeyeon and Overcash, Michael (2001). Life-cycle assesment study of color computer monitor. *Int. J. LCA*, *6*(1), 35–43.

Shah, V. P., Debella, D. C., and Ries, R. J. (2008). Life cycle assessment of residential heating and cooling systems in four regions in the United States. *Energy Build.*, 40(4), 503–513. doi:10.1016/j.enbuild.2007.04.004

Frey, Sibylle D., Harrison, David, J. and Billett, Eric H. (2006). Ecological footprint analysis applied to mobile phones. *J. Ind. Ecol.*, 10(1-2), 199–216.

Socolof, M. L., Overly, J. G., and Geibig, J. R. (2005). Environmental life-cycle impacts of CRT and LCD desktop computer displays. *J. Cleaner Prod.*, 13(13-14), 1281–1294. doi:10.1016/j.jclepro.2005.05.014

Song, Q., Wang, Z., Li, J., and Yuan, W. (2012). Life cycle assessment of desktop PCs in Macau. *Int. J. Life Cycle Assess.*, 18(3), 553–566. doi:10.1007/s11367-012-0515-7

Song, Q., Wang, Z., Li, J., and Zeng, X. (2012). Life cycle assessment of TV sets in China: A case study of the impacts of CRT monitors. *Waste Manage*, 32(10), 1926–1936. doi:10.1016/j.wasman.2012.05.007

Stiel, F., and Teuteberg, F. (2014). Measuring the environmental impact of IT/IS solutions—A life cycle impact modelling approach. *Environ. Model. Software*, 56, 94–104. doi:10.1016/j.envsoft.2013.12.014

Streicher-Porte, M., Marthaler, C., Boni, H., Schluep, M., Camacho, A., and Hilty, L. M. (2009). One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia. *J. Environ. Manage.*, 90(11), 3498–3511. doi:10.1016/j.jenvman.2009.06.002

Stutz, M., and O'Connell, S. (2010). Product carbon footprint (PCF) assessment of dell laptop—Results and recommendations. *IEEE Sustainable Syst. Technol.*, 1–6.

Tagami, T., and Williams, E. (2003). Energy use in sales and distribution via e-commerce and conventional retail—A case study of the Japanese book sector. *J. Ind. Ecol.*, *6*(2), 99–114.

Taiariol, F., Papuzza, C., Cultrera, S., Antonetti, M., and Cerioni, S. (1999). Environmental impact and end of life management of telephone exchange equipment. *IEEE*, 64–69.

Tasaki, T., Motoshita, M., Uchida, H., and Suzuki, Y. (2013). Assessing the replacement of electrical home appliances for the environment. *J. Ind. Ecol.*, 17(2), 290–298. doi:10.1111/j.1530-9290.2012.00551.x

Taticchi, P., Garengo, P., Nudurupati, S. S., Tonelli, F., and Pasqualino, R. (2014). A review of decision-support tools and performance measurement and sustainable supply chain management. *Int. J. Prod. Res.*, 1–22. doi:10.1080/00207543.2014.939239

Techato, K.-A., Watts, D. J., and Chaiprapat, S. (2009). Life cycle analysis of retrofitting with high energy efficiency air-conditioner and fluorescent lamp in existing buildings. *Energy Policy*, 37(1), 318–325. doi:10.1016/j.enpol.2008.08.021

Teehan, P., and Kandlikar, M. (2013). Comparing embodied greenhouse gas emissions of modern computing and electronics products. *Environ. Sci. Technol.*, 47(9), 3997–4003. doi:10.1021/es303012r

Teehan, P., and Kandlikar, M. (2011). Sources of Variation in Life Cycle Assessments of Desktop Computers. *Journal of Industrial Ecology*, 16 (S1), S182–S194.

Thomas, N. J., Chang, N.-B., and Qi, C. (2011). Preliminary assessment for global warming potential of leading contributory gases from a 40-in. LCD flat-screen television. *Int. J. Life Cycle Assess.*, 17(1), 96–104. doi:10.1007/s11367-011-0341-3

Vasan, A., Sood, B., and Pecht, M. (2014). Carbon footprinting of electronic products. *Appl. Energy*, 136, 636–648. doi:10.1016/j.apenergy.2014.09.074

Coroama, Vlad C., Moberg, Å., and Hilty, Lorenz M. (2014). Dematerialization through electronic media. *Adv. Intell. Syst. Comput.*, 310.

Wager, P. A., Hischier, R., and Eugster, M. (2011). Environmental impacts of the swiss collection and recovery systems for waste electrical and electronic equipment (WEEE): A follow-up. *Sci. Total Environ.*, 409(10), 1746–1756. doi:10.1016/j.scitotenv.2011.01.050

Weber, C. L. (2012). Uncertainty and variability in product carbon footprinting. *J. Ind. Ecol.*, 16 (2), 203–211. doi:10.1111/j.1530-9290.2011.00407.x

Whitehead, B., Andrews, D., Shah, A., and Maidment, G. (2014). Assessing the environmental impact of data centres part 1: Background, energy use and metrics. *Build. Environ.*, 82, 151–159. doi:10.1016/j.buildenv.2014.08.021

Williams, E. (2004). Energy intensity of computer manufacturing hybrid assessment combining process and economic input-output methods. *Environ. Sci. Technol.*, 38, 6166–6174.

Wu, R., Yang, D., and Chen, J. (2014). Social life cycle assessment revisited. *Sustainability*, 6(7), 4200–4226. doi:10.3390/su6074200

Xiao, R., Zhang, Y., Liu, X., and Yuan, Z. (2015). A life-cycle assessment of household refrigerators in China. *J. Cleaner Prod.*, 95, 301–310. doi:10.1016/j.jclepro.2015.02.031

Yanagitani, K., and Kawahara, K. (2000). LCA-study-of-air-conditioners-with-an-alternative-refrigerant. *Int. J. LCA*, 5(5), 287–290.

Yang, J.-X., Wang, R.-S., Fu, H., Liu, J.-R. (2004). Life cycle assessment of mobile phone housing. *Journal of Environmental Sciences*, 16(1), 100–103.

Yokota, K., Matsuno, Y., Yamashita, M., and Adachi, Y. (2003). Integration-of-life-cycle-assessment-and-population-balance-model-for-assessing-environmental-impacts-of-product-population-in-a-social-scale. *Int. J. LCA*, *8*(3), 129–136.

Yu, J., Williams, E., and Ju, M. (2010). Analysis of material and energy consumption of mobile phones in China. *Energy Policy*, 38(8), 4135–4141. doi:10.1016/j.enpol.2010.03.041

Yung, W.K.C., Chan, H. K., So, J.H.T., Wong, D.W.C., Choi, A.C.K., and Yue, T. M. (2011). A life-cycle assessment for eco-redesign of a consumer electronic product. *J. Eng. Des.*, 22(2), 69–85. doi:10.1080/09544820902916597

Yung, W.K.C., Chan, H. K., Wong, D.W.C., So, J.H.T., Choi, A.C.K., and Yue, T. M. (2008). Life cycle assessment of two personal electronic products—A note with respect to the energy-using product directive. *Int. J. Adv. Manuf. Technol.*, 42(3-4), 415–419. doi:10.1007/s00170-008-1606-2

Yung, W.K.C., Chan, H. K., Wong, D.W.C., So, J.H.T., Choi, A.C.K., and Yue, T. M. (2012). Eco-redesign of a personal electronic product subject to the energy-using product directive. *Int. J. Prod. Res.*, 50(5), 1411–1423. doi:10.1080/00207543.2011.571941

Zhang, H. C., Li, J., Shrivastava, P., Whitley, A., and Merchant, M. E. (2004). A web-based system for reverse manufacturing and product environmental impact assessment considering end-of-life dispositions. *CIRP Ann. Manuf. Technol.*, 53(1), 5–8. doi:10.1016/s0007-8506(07)60632-5

Zhou, X., and Schoenung, J. M. (2007). An integrated impact assessment and weighting methodology: Evaluation of the environmental consequences of computer display technology substitution. *J. Environ. Manage.*, 83(1), 1–24. doi:10.1016/j.jenvman.2006.01.006

Zink, T., Maker, F., Geyer, R., Amirtharajah, R., and Akella, V. (2014). Comparative life cycle assessment of smartphone reuse: Repurposing vs. refurbishment. *Int. J. Life Cycle Assess.*, 19(5), 1099–1109. doi:10.1007/s11367-014-0720-7