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Rochester Institute of Technology

A Research Monograph of the Printing Industry Center at RIT

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Abstract

Life Cycle Assessment (LCA) is the leading tool for estimating environmental effects of products and processes. Despite this wide use, LCA analysis remains problematic and limited. Within the printing industry, one of the primary problems is non-standardized assumptions and practices. This makes it difficult, if not impossible, to compare the life cycle impacts of products. This paper will compare LCA studies performed within the printing industry in order to identify common practices, limitations, areas for improvement, and opportunities for standardization. This comparison is focused on the data sources and methodologies used in the particular studies.

Introduction

Printing is an ubiquitous part of our lives, ranging from the printing of personal documents and photos, to the documents we use to communicate in business and the mass production of advertisements, marketing, and magazines. Given the pervasiveness of print, it is not surprising that many organizations are interested in the environmental impacts associated with printing through its life cycle. These include impacts such as deforestation, toxic pollution, water consumption, energy consumption, solid waste production, and air pollution. For example, 42% of the world's harvested industrial wood is used to make paper (World Resources Institute, United Nations Environment Programme, United Nations Development Programme, & The World Bank, 1998). Within the forest products industry, the pulp and paper industry uses 84% of the energy consumed by the forest products industry (U.S. Energy Information Administration [EIA], 2006). A Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Association ranked the industry as a whole as the third largest industrial consumer of energy, ranked only behind the petroleum and chemicals industries (EIA, 2006). Given these impacts, a clearer understanding of the life cycle environmental impacts of printing would naturally be of interest.

Life Cycle Assessment (LCA) had its early beginnings in the printing arena, with a focus on packaging; the first internal LCAs were performed by Coca-Cola in the early 1970s (Graedel, 1998). Early LCA databases focused on packaging to improve materials choice. Since then, LCAs have been performed by almost every major print equipment provider on a range of devices (Lexmark, 2010; Koehler, Latko, & Stocum, 2010; Ord, Canonico, Strecker, & Chappell, 2009; Ricoh Group, 2009; Canon Inc., 2010). While LCA is a widely used tool, it still has its drawbacks, such as expansive data requirements and high associated costs (Reap, Roman, Duncan, & Bras, 2008a). One potential mechanism to reduce these problems is to develop LCA standards. Initial attempts to standardize LCA processes have been made by the International Organization for Standardization ([ISO], 2006a, 2006b) and the Society of Environmental Toxicology and Chemistry (Beaufort-Langeveld, Bretz, van Hoof, Hischier, & Tanner, 2003). These codifications are meant to establish basic guidelines while remaining broad enough to be applicable to a wide variety of practitioners.

The Electronic Product Environmental Assessment Tool (EPEAT) has taken a different approach (IEEE 1680). Realizing that each industry has certain areas of major impact and assumptions specific to that industry which would carry little weight elsewhere, it has established product-specific standards. The U.S. ENERGY STAR certification program is another widely recognized certification program that has led to the wide acceptance of industry-specific Typical Electricity Consumption (TEC) procedures, which has helped to standardize energy use calculations (U.S. Environmental Protection Agency [EPA], 2006, 2008).

In addition to the standardization of impact assessment methods, there are also commonly used standards that quantify specific life cycle impact categories. For example, the Intergovernmental Panel on Climate Change is frequently cited for 50- and 100-year greenhouse gas (GHG) equivalent carbon dioxide (CO_2e) calculations (Intergovernmental Panel on Climate Change [IPCC], 2006), as is the British Standards Institution's Publicly Available Specification 2050 (PAS 2050) on GHG emissions (British Standards Institution [BSI], 2008).

Despite these standards and certification programs, there is still a great deal of uncertainty and disagreement about the interpretation of the many LCA studies in the printing industry. In this paper, several LCA studies are compared in order to identify common practices, limitations, and areas for improvement and standardization.

Methodology

Analysis

The life cycle assessment framework specified by ISO 14040 is shown in Figure 1. The categories shown in the framework will serve as the basis for conducting the comparisons that follow, which are the goal and scope, the inventory analysis, the impact analysis, and the interpretation of the results. The comparison of goal and scope includes the study context, the delineation of the functional unit, definition of the system boundaries, and determination of the printer system items under consideration. It is important to note differences between traditional LCAs and decision tools such as Score Cards, hybrid LCA, and Streamlined LCA (SLCA). Inventory analysis includes both Life Cycle Inventory (LCI) and Life Cycle Inventory Allocation (LCIA). Comparison in this phase is focused on the data sources used and on the methodologies used in these particular studies. The comparison of impact assessment will focus largely on the particular impact categories selected and how they relate to the original goal and scope of their study. Lastly, the weighting of impact categories and a comparison of how these results were interpreted will be discussed, followed by a short discussion on the importance of the critical review.

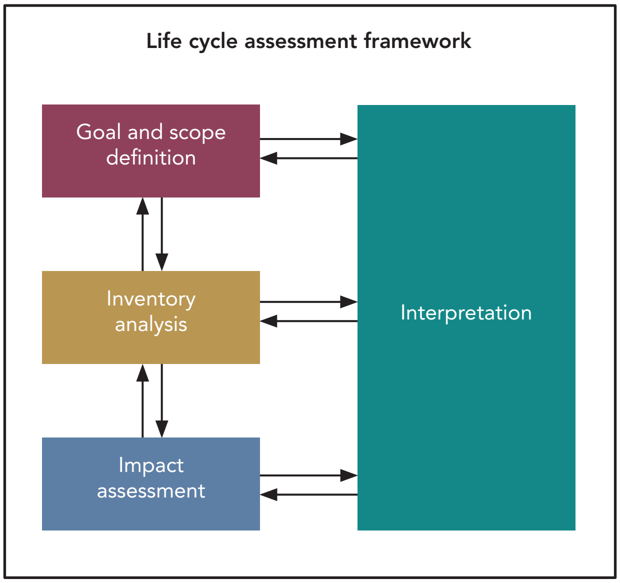

Figure 1. Life cycle assessment framework from ISO 14040

Scope of Study

Since the focus of this research is the printing industry, the studies were selected because they either included imaging equipment or were highly relevant to imaging equipment. The term "imaging equipment" is defined in the energy-using products (EuP) preparatory studies as "commercially available product which was designed for the main purpose of producing a printed image (paper document or photo) from a digital image through a marking process" (Stobbe, 2007, p. 12). Table 1 summarizes the studies; they are described in greater detail below. It should be noted that while pulp and paper production are clearly an important contributor to the life cycle impacts of printing, explicit studies of these industries are not included in this review since their impacts are typically accounted for in the studies reviewed in this work. For the interested reader, paper and pulp industry LCAs such as those by Dias, Arroja, and Capela (2007) and Miner (2010) provide excellent reviews of paper and pulp industry LCA analyses.

Table 1. Studies analyzed

Category/#	Short title	Author & Year	Product	Purpose
Printers				
[1]	Product Environmental Metrics for Printers	Ord et al. 2009	Printers	Internal design tool
[2]	Solid Ink LCA	Koehler et al. 2010	Solid ink and ink jet printers	Comparative LCA
[3]	Eco-efficiency Gains From Re-manufacturing	Kerr & Ryan 2001	Photocopier remanufacture	Comparative LCI: Reuse vs. new
[4]	Extended Producer Responsibility for Waste Electronics	Mayers et al. 2005	HP printers	Comparative LCA: End-of-life
[5]	EuP Preparatory Studies "Imaging Equipment"	Stobbe 2007	EP & IJ printers, copiers and MFDs	Industry baseline LCA
Cartridges				
[6]	LCA Toner Cartridge C4127X	Berglind & Eriksson 2002	HP cartridge C4127X	Comparative LCA: Remanufacture
[7]	LaserJet Cartridge Life Cycle Refresh Study	Four Elements Consulting 2008	HP LJ 10A and remanufactured cartridges	Comparative LCA: Remanufacture
[8]	Life Cycle Inventory of Toner for Xerographic Processes	Ahmadi et al. 2003	Toner	LCI of toner
Print products				
[9]	Life Cycle Carbon Footprint of the National Geographic	Boguski 2009	Magazine	Carbon footprint
[10]	LCA: Flexographic and Rotogravure Printing	Veith & Barr 2008	Packaging materials printing	Comparative LCA
Design methodologies/Tools				
[11]	Methodology for the Evaluation of Product Sustainability at the Design and Development Stage	Silva et al. 2006	Not applicable	Design stage sustainability scoring
[12]	Development of a Green Scorecard	Ebner et al. 2009	Printers	Design directional indicator
Consumer "calculators"				
[13]	HP Carbon Footprint Calculator for Printing	Hewlett-Packard 2009	Personal and office printers	Cost and carbon calculator
[14]	Xerox Sustainability Calculator	Xerox 2008	Personal and office printers	Compare baseline and optimized print scenarios

A subset of studies include commercially available consumer and business products:

1. Hewlett-Packard's (HP) Imaging and Printing Group (IPG) reported on the development process undertaken to establish the initial internal metrics that will guide design, chart progress, and set environmental goals for their printer products (Ord et al., 2009).
2. The Xerox Solid Ink LCA white paper serves as a quick overview of a comparison study performed on a color solid ink multifunction printer and a comparable color laser multifunction printer (Koehler et al., 2010).
3. "Eco-Efficiency Gains from Remanufacturing" (Kerr & Ryan, 2001) investigates whether remanufacturing could reduce the resource intensity of a product system. This study was not intended to assess the overall life cycle environmental impacts of a photocopier or the remanufacture of such products; however, LCA processes and delineations were adhered to.
4. Life cycle assessment and costing are used to explore some of the possible environmental impacts that may result due to the mass-based recovery and recycling targets established under the European Union's (2003a) Waste Electrical and Electronic Equipment (WEEE) directive, based on a case study of HP printer recycling in the United Kingdom (Mayers, France, & Cowell, 2005). Specific environmental objectives and standards for treatment and recycling processes are suggested as an alternative to this mass-based approach.
5. The EuP Preparatory Studies on imaging equipment are the result of extensive research conducted by the Fraunhofer IZM consortium with the collaboration of industry and stakeholders (Stobbe, 2007). The study is rather extensive, going into much greater detail than typical LCAs on definitions of products, markets, assumptions, trends, and opportunities for improvement and policy. As a result, the study may serve as an important resource for printing industry LCA practitioners.

LCA studies of print consumables such as ink, toner, and cartridges were included as another subset. The remanufacture and reuse of toner cartridges has garnered particular interest and debate. These studies included:

6. One of the first LCAs to assess the environmental impact of cartridge remanufacture and reuse for laser printers was Berglind and Eriksson (2002). The environmental impact of an original HP C4127X toner cartridge and its disposal according to HP's process at the time was compared to the remanufacture and reuse of the same cartridge at Tepro Rebuild Products AB.
7. Four Elements Consulting revisited the 2004 First Environment LCA study, which again compared a popular HP Laser Jet print cartridge to the average compatible remanufactured one. This version of the study updated data related to the production/remanufacturing practices, end-of-life trends, and product

quality and reliability (Four Elements Consulting, 2008). The most significant update was from data gathered during a 2007 Quality Logic reliability comparison study. This study examined differences in print quality page acceptance between original and remanufactured toner cartridges. The reason this is an important consideration is that paper consumption dominates the environmental impact of the printing process, and increases in reprinting due to unacceptable print quality increases this consumption.

8. The study by Ahmadi, Williamson, Theis, and Powers (2003) presents results of a Life Cycle Inventory (LCI) of toner used in the xerographic process. Specifying a print system consumable for study only to the point of inventory allows for greater depth of data collection, and results can potentially be included in the use phase of future printer LCA studies if approached correctly.

In addition to the commercially available consumer and business products, two studies were included that examined commercial printing applications. These commercial printing process comparisons were included to highlight similarities and differences with the environmental issues faced by this sector of the printing industry.

9. Although there are published assessments of newspapers, books, and other magazines (e.g., Gower et al., 2006), only that of the National Geographic is included in this study as it includes the print process in its supply chain. This study serves as an excellent example of how increased collaboration upstream and downstream can improve data relevancy. National Geographic, Verso Paper, and Quad Graphics all provided high quality data to account for GHG emissions throughout the life cycle of the magazine (Boguski, 2010). This allowed for the most significant improvement opportunities to be identified within paper manufacturing and printing.

10. DuPont's LCA compares two commercial print processes—flexography and rotogravure. The study is meant to provide insight for the value chain and to support customer decision making (Veith & Barr, 2008). Markets for these two print processes have been increasingly overlapping with quality improvements in flexographic technology, making them more comparable.

Though this review focused on LCAs, there is industry interest in streamlining tools and making them more effective for design and/or the decision-making process. Design practitioners face even greater difficulties with data uncertainty, as often the assessment must be performed before any significant development of the product and in the presence of scarce data (Ben-Haim, 2006; Duncan, Bras, & Paredis, 2008). Therefore, several tools that are simplified for decision making and that only examine one impact category—such as the green scorecard or carbon footprint calculators—were also included, provided that a life cycle approach was taken in the study.

11. A study by Silva, Jawahir, Dillion, and Russell (2006) develops a qualitative streamlined "Sustainability Scoring" method for design stage decisions. Six elements are defined: Environmental impact, societal impact, functionality, resource utilization and economy, manufacturability, and recyclability/re-manufacturability, within which ten sub-elements are selected and weighted for evaluation. The study compares how design practitioners and consumers place different levels of importance on these elements.
12. Xerox's Green Scorecard is neither a design tool nor a substitute for LCA; rather, it is meant to guide selection of eco-efficiency research opportunities in digital printing. It is based on quantified input data for six criteria and was validated using LCA results (Ebner, Chang, Knapp, Deyoung, & Latko, 2009).

Office and consumer customers are interested in knowing how their printers are impacting the environment and how they can reduce this impact. Some device manufacturers now offer online calculators where users can input certain criteria and receive suggestions on ways to reduce their environmental impact. Two online calculators comprised the fifth and final subset of studies included:

13. The HP Carbon Footprint Calculator for printing gives users a use-phase estimate of the electricity cost and corresponding CO_2e emissions that result from the production of that electricity (Hewlett-Packard Development Company [HP], 2009). The cost and carbon footprint of the paper used is also estimated. The footprint results can be converted into equivalent miles or km driven in an automobile, putting the results into perspective for users.
14. The Xerox Sustainability Calculator is not based on specific brands or models; rather, it is meant to compare customer baselines with an optimized print option (Xerox Corporation, 2008). Xerox representatives are available to offer customers actual optimization scenarios with more varied input variables.

Findings

Goal and Scope

Context

The goal of a particular Life Cycle Assessment (LCA) is essential to identify and assess impacts to be examined, omissions that need to be made, and other basic underlying assumptions. The descriptions of the studies identified in the prior section briefly described the goal of each study, but the context within which the study was conducted is equally important, as it also plays a role in the decision-making process (Wenzel, 1998). Organization affiliation and the intended use of the studies are two characteristics that have been used in this paper to identify the context of these studies. Organizational affiliation refers to the sector from which the practitioner who conducted the LCA came from, namely academia, industry external (consultant), or industry internal. The second characteristic refers to the intended audience, which is either "Internal Design," "External Marketing", or to establish a general "Baseline" for comparison of two or more alternative technologies. These results are summarized in Table 2 and Table 3.

While the results in Table 3 cannot be considered representative of all studies, it should be noted that academic studies were primarily conducted to establish baselines or for internal design purposes. In addition, no studies that were conducted by external consultants were used for internal design purposes, while the majority of the studies that were conducted for external marketing were reviewed by academia or a consultant.

Table 2. Study context

Study #	Organization affiliations	Practitioner	Audience
[1]	Hewlett-Packard	Industry Internal	Internal – Design
[2]	Xerox (RIT Review)	Industry Internal	External – Marketing
[3]	Lund University, Melbourne Institute of Technology, Fuji-Xerox	Academia	Internal – Design
[4]	University of Surrey (HP Data)	Academia	Baseline
[5]	Fraunhofer IZM	Academia	Baseline
[6]	Kalmar, Black and Write	Academia	Baseline & Marketing
[7]	Hewlett-Packard, Four Elements Consulting	Industry External	Baseline & Marketing
[8]	Clarkson University (Xerox Data)	Academia	Baseline
[9]	Harmony Environmental, National Geographic, Verso Paper, Quad Graphics	Industry External	Baseline & Marketing
[10]	DuPont, Five Winds International (Review)	Industry Internal	Baseline & Marketing
[11]	University of Kentucky, Lexmark	Academia	Internal – Design
[12]	Xerox	Industry Internal	Internal – Design
[13]	Hewlett-Packard	Industry Internal	External – Marketing
[14]	Xerox, consultants	Industry External	External – Marketing

Table 3. Summary of study context

Affiliation	Intended audience		
	Internal – Design	External – Marketing	Baseline
Academia	2	1	4
Industry Internal	2	3	1
Industry External	0	3	2

Scope

The scope of the LCA is an early decision with great significance. As noted by Reap et al. (2008a), "Foundational decisions about the basis of comparison (functional unit), bounds of the study, and physical relationships between included processes largely dictate the representativeness and, therefore, the value of an LCA" (p. 290). This section of the paper will compare the functional unit and system boundaries decisions made in the studies identified in the prior section.

Functional Unit

The functional unit is essential, as it defines the output by which products will be compared. All of the analysis parameters are, therefore, normalized to it. ISO defines the functional unit as the "quantified performance of a product system for use as a reference unit" (ISO 14044:2006), and it is "necessary to ensure comparability of LCA results" (ISO 14040:2006). Defining a functional unit is made more complex by the multitude of functions a particular product can perform for a consumer. For example, multifunctional devices (MFD) combine scanning, faxing, copying, and printing into one machine rather than multiple machines. Intuitively, one would assume that this would be environmentally beneficial, reducing the materials requirement and minimizing the energy consumptions while idle. In addition, the factors that affect the purchase decision, such as aesthetics or size, must also be accounted for when defining the functional unit.

A short description of the functional unit defined in each study in presented in Table 4. Given that the studies examine closely related products, one might conclude that the functional units defined would also be closely related and would not inhibit cross-comparisons. There are many specific characteristics that must be consistent, however, or the results will not be comparable. For example, the printing speed, typically designated as prints per minute (PPM), is sometimes omitted, yet it is directly related to energy consumption (Stobbe, 2007). Other factors which contribute to the increased consumption of paper should also not be overlooked, as the cumulative consumption of paper over the useful life of the printer becomes very important. Table 5 outlines the different assumptions for device useful period used in comparisons. Allowing for comparisons of alternatives that lead to reduced consumption of paper often requires functional units that are flexibly defined to include both paper and other communications media. For example, in Xerox's Green Scorecard, a comparison can be made on the basis of units of information being conveyed (Ebner et al., 2009).

Table 4. Study functional unit comparison

Study #	Product(s)	Purpose	Stated functional unit
[1]	Printer devices	Internal design tool	Per image printed. Considers expected life of print system and images printed per month.
[2]	Solid ink vs. ink jet printer	Comparative	25,000 prints/month over a four-year life.
[3]	Manufactured vs. remanufactured copiers	Comparative	12 million copies over a maximum period of 10 years for each life cycle.(1)
[4]	3,250 imaging devices	Comparative (End-of-life)	21.6 tonnes printer waste.
[5]	Electrophotographic and ink jet printers, copiers and multifunctional devices	Baseline	Average daily use pattern (pages/job, number of jobs and idle time, on- and off-mode time).
[6]	Cartridge remanufacture	Comparative	"30,000 copies with 5% average coverage." The duration is 1 year. (2)
[7]	Cartridge remanufacture	Comparative	Printing of 100 usable monochrome one-sided pages. Consistent with Quality Logic study. 6,000 pages in accordance with ISO.(3)
[8]	Toner	Baseline	One metric ton of toner produced - enough to produce an average of 22 million images on A4 with 6% coverage.
[9]	Magazine	Baseline	One magazine, avg weight of 349 g.
[10]	Flexographic and rotogravure packaging print processes	Comparative	Area of imaged plate or printed substrate.
[11]	No product evaluated	Design tool development parameters	Over 5 functional years.(4)
[12]	Printers (non- specific)	Design tool	A unit of information: A4 impression of average area coverage (5-6% per color). 10 million units of information.
[13]	Personal and office printers	Cost and CO_2e calculator	Variable, pages printed per year and printer life.
[14]	Personal and office printers	Compare baseline and optimized print scenarios	Number of images per month; results are annualized.

(1) Study compared life cycles of manufactured vs. remanufactured devices, but these were the use-phase assumptions that could have been used as a possible functional unit.

(2) Allows comparison of new cartridge versus a remanufactured cartridge which can be refilled 3 times in a year assuming a 30,000 page yield and 10,000 page monthly use volume.

(3) ISO/IEC 19752.

(4) Not directly stated in study. Evaluates alternatives during design, no comparison performed.

Table 5. Device useful period (InfoTrends data as shown in Stobbe, 2007)

Device	Life cycle (1)	Retirement period (2,3)
Electrophotographic printer (monochrome)	2-3 years	3-5 years
Electrophotographic printer (color)	2-3 years	4-5 years
Copier (monochrome)	2-4 years	4-5 years
Copier (color)	2-3 years	4 years
Ink jet printer	2-3 years	3-5 years
Facsimile machine	2 years	4 years

(1) Life Cycle is the period of time where the device is expected to be in use.

(2) Retirement period is the number of years between production and disposal, as devices are slowly retired.

(3) The number of devices is considered to gradually decrease by 1/3 each year over this retirement period.

An alternative to using years is to measure the number of images or documents over the life of the equipment. This option has the advantage of allowing easier comparison of machines with higher and lower outputs. One commonly cited number is that the typical office employee prints 10,000 pages per year (Australian Government Department of Families, Housing, Community Services and Indigenous Affairs [FaHCSIA], 2007). The EuP recognized a need for market and usage pattern data and addressed these issues in their initial report. Table 6 summarizes some of these data, based on an InfoTrends report. These results were based on a large pool of units but were averaged to the printer unit rather than per employee.

Table 6. Printer usage patterns (InfoTrends data as shown in Stobbe, 2007)

Imaging equipment	Average output 2005 (1 year) (1)	Device composition (2,3)		Number of units
Electrophotographic printer	26,360 pages/unit (2197 pages/month)	12% color	88% B&W	16,654
Electrophotographic copier	16,218 pages/unit (1352 pages/month)	6% color	94% B&W	6,351
Ink jet printer	876 pages/unit (73 pages/month)	3% MFD	97% printer	90,172
Ink jet copier	1,440 pages/unit (120 pages/month)	34% MFD	66% copier	20,131

(1) Page output was averaged over the total number of units for the year.

(2) Electrophotographic equipment included both color and black and white.

(3) Ink jet equipment included some multifunctional devices.

With these usage data in mind, a closer comparison of the assumptions behind the functional units used in the studies is insightful. Table 7 shows the studies which have functional units that are dependent on, or include, a page output. When considering page outputs, it is important also to consider the type of printer and its speed (PPM). When considered with the usage period, a direct comparison is facilitated.

Table 7. Printer usage assumptions*

Study #	PPM (1)	Printer type	Pages	Pages/Month	Average coverage	Time period (2)
[6]	17	LaserJet	30,000	2,500	5%	1 yr (3 cartridges)
[7]	25	LaserJet	100	Not available	Not available	Not available
[2]	50	Color laser MFD	1,200,000	25,000	5-6%	4 yrs (1 device)
[3]	100 (3) 65 (4)	5100 B&W copier DC 265 B&W copier	12,000,000	100,000	Not available	10 yrs max (6)
[8]	135	B&W copier (5)	22,000,000	611,111	6%	3+ yrs (6)
[12]	User input	User input	10,000,000	Not available	5-6%	User input
[1]	User input	User input	User input	Not available	Not available	User input
[13]	User input	User input	User input (10,000) (7)	Not available (833) (7)	Not available	User input (5 yrs) (7)
[14]	User input	User input	User input	Not available	Not available	Results annualized

* "Not Available" data are those that were not provided in the publications or reports. "User Input" data are variable data that the tool user must enter at the beginning of the assessment.

(1)Printer speed is indicated by prints per minute (PPM).

(2)Time periods are either the time limitations on the study or the expected useful life of the devices being studied.

(3)Xerox 5100 Copier specifications.

(4)Xerox Document Centre 265 Digital Copier specifications.

(5)Xerox (1997) Product Safety Data Sheet.

(6)Limit on imaging device useful life.

(7)These are the default settings used.

The monthly outputs in Table 6 are small compared to those used in the studies (see Table 7). Stobbe (2007) did not include the images per minute (IPM) for these device results. However, several other electrophotographic printers and copiers in the EuP study used assumptions of 30 IPM and 26 IPM, respectively. These print rates are comparable to those in studies 6 and 7.

HP's carbon calculator has a variable functional unit set by the user (HP, 2009). The functional unit terms, years of device operation, and number of pages printed per year can be set to match the users' perceived actual usage parameters. In many cases the users may not know their actual usage patterns, so defaults of 10,000 prints per year and a five-year useful life are used. Upper limitations are placed on the annual pages corresponding to the number of pages that could be printed at the device's speed over 8 hrs/day, 5 days/week, for 52.2 weeks/year.

Another important consideration is the push for paperless communications. Providing the user with paperless options allows the print or digital decision to be made on a case-by-case basis depending on the user's needs and preferences. The importance of this trend is that it creates a need for functional units which allow for comparisons between these two forms of communications. By employing approaches such as "information per unit of paper mass," these types of comparisons will be enabled, allowing such studies to remain relevant when compared to new media (Hischier & Reichart, 2003).

System Boundaries

To label an assessment tool as a "life cycle assessment" inherently suggests that the entire life cycle of the product will be examined for environmental impacts. For the purposes of this paper, life cycle "stages" refers to the cradle-to-grave process, from the acquisition of the raw materials through production, use, and eventual end-of-life disposition (reuse, remanufacture, recycle, disposal). Accurately quantifying all flows in and out of the product system would be extremely costly and time-intensive. In consideration of these concerns, system boundaries are set to distinguish which impacts will be included. Inappropriate boundary selection poses a risk that LCA results will not sufficiently reflect reality, leading to incorrect interpretations (Graedel, 1998).

Most of the studies examined, including the design decision tools, do consider inputs from all stages of the product life cycle. This does not mean, however, that all inputs from each stage are accounted for. In addition, the depth to which the environmental impacts for these inputs are accounted for is also varied. Reap et al. (2008a) described four approaches for addressing boundary selection problems: qualitative or semi-quantitative approaches, quantitative approaches guided by data availability, quantitative process-based approaches that use more refined cutoff criteria, and input-output-based approaches. These four approaches are evident to some extent in the selected studies.

The main life cycle stage delineations used in this paper have been taken from ISO 14040:2006 and are shown in Figure 2. Two modifications were made in adopting Figure 2 for this analysis as seen in Table 8 and Appendix A. Packaging has been separated from the production stage since it was an important consideration in some studies, particularly those focusing on consumables. Likewise, transportation was separated out because several studies focused on reuse and remanufacture, where equipment must be collected and transported to be remanufactured. Both transportation and packaging are included in multiple stages, meaning that inclusion isn't always directly stated. A case could be made for separating out energy supply, considering the significance of the impact associated with this component; however, all of the studies included this component to some degree.

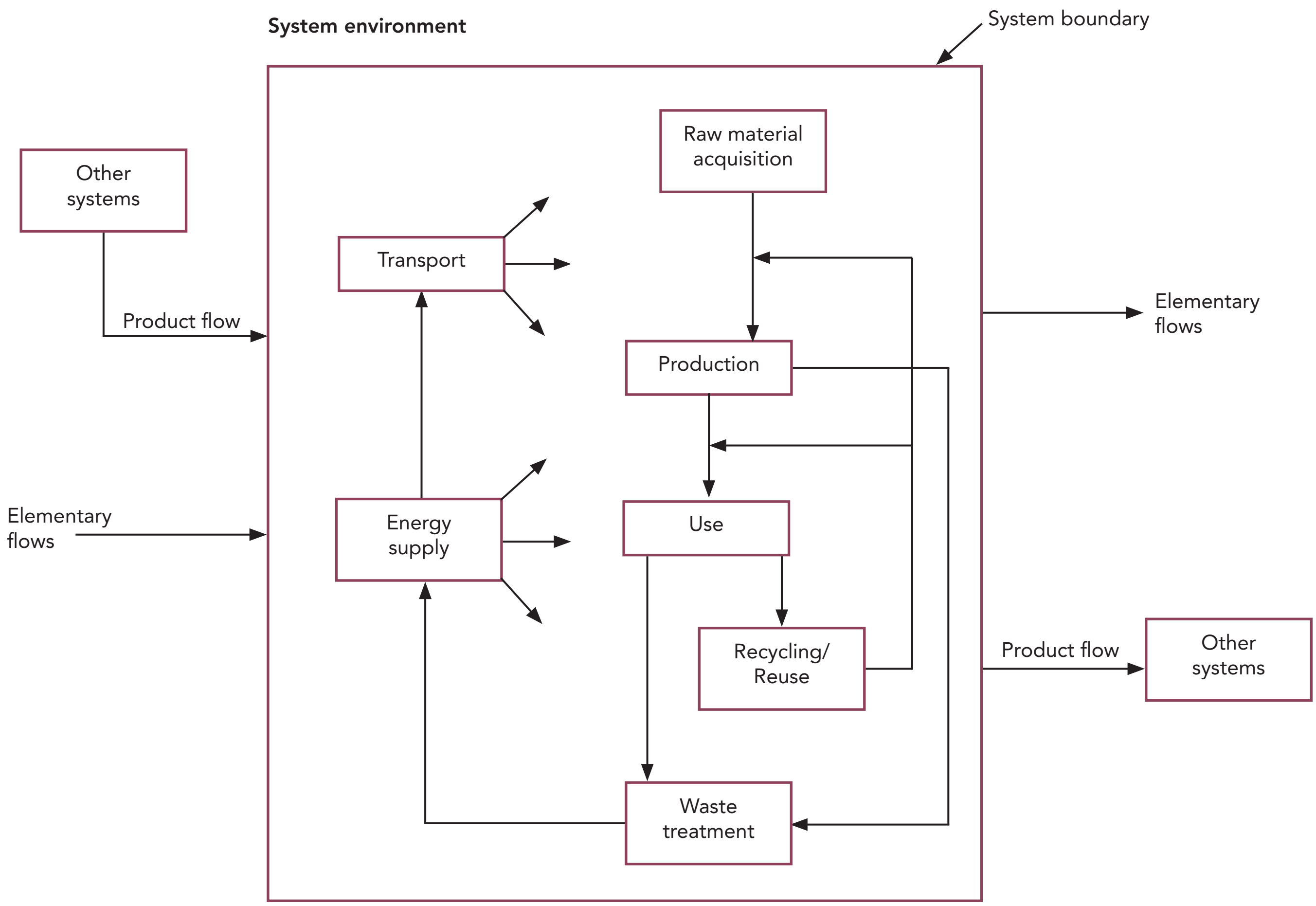

Figure 2. System environment with the five main life cycle stages (adapted from ISO 14040:2006)

In addition to the system boundaries, which represent the breadth of the data in the respective studies, the quality of the data is also of importance. The National Geographic life cycle carbon footprint study serves as an example of how multiple parts of the supply chain can collaborate to develop a better assessment, collecting data with greater breadth, depth and accuracy (Boguski, 2010). Harmony Environmental Consulting assisted in combining a study Verso Paper had previously conducted with a new study from Quad Graphics and National Geographic (Boguski, 2010). Another criticism of LCA is that the quantitative data used is limited spatially and temporally. All data used in the National Geographic carbon footprint study was specific to a two-year span of time, and regional data were weighted to the percentage of activities that actually took place there.

For each study, a short description of data collected during each stage of the life cycle is shown in tabular format in Appendix A. From this table a loose grading system of A to E, similar to that used in Boguski (2010), was used to evaluate the level of detail at which each life cycle stage was explored. Some studies were missing parts of production, such as assembly, or were simply basing impacts on bill-of-material masses. The results of this grading effort are shown in Table 8.

Table 8. Graded life cycle stage data

Stage	Cartridge Remanufacture		Baseline Academia		Comparative		Design Tools			Calculators		Baseline Industry		
	[6]	[7]	[5]	[4]	[10]	[2]	[11]	[12]	[1]	[13]	[14]	[3]	[9]	[8]
Raw Materials	B	B	C	C	B	B	B	C	B	D	C	C	A	B
Production	B	C	C	E	B	B	E	C	B	C	C	C	A	A
Transportation	B	B	B	E	C	B	E	B	C	D	D	C	B	B
Use	B	B	B	E	A	B	B	B	C	B	C	E	E	B
End-of-life	B	B	B	B	C	B	B	B	C	D	C	B	B	B
Packaging	B	B	C	B	D	B	B	C	E	D	B	D	E	C

Explanation of Grades:

A - Primary data measured on site during the phase. All relevant aspects seem to have been accounted for.

B - Database data or literature-referenced data. May be missing part of a process.

C - Incomplete data or estimates, but still representative of some impacts in this stage.

D - Stage was not included in study scope.

E - NA, was excluded due to lack of applicability to study goals.

There are no definite trends concerning life cycle stage omissions. Transportation and packaging were lacking high-quality data or ignored in many of the studies. Raw materials acquisition was missing in the greatest number of studies, likely because the practitioners faced difficulties in obtaining upstream data. When it was included, the typical approach to raw materials acquisition and component manufacture by suppliers was to retrieve database impact attributes based on masses from a bill of materials obtained by disassembling the product, as can be seen in Appendix A.

Also, it is difficult for practitioners to determine adequate upstream cutoffs, as many times there are unknown processes involved in the production of component materials. Surprisingly, considering the difficulty in accurately estimating it, the end-of-life stage was the most populated. This is partly due to the focus of design tools on reuse and recyclability. Given the difficulty in estimating actual end-of-life practices, none of the core studies could be given an "A" for this stage. Trends in each stage are discussed in the following sections.

Materials Acquisition Stage

Accounting for the raw materials and energy use that occur upstream in the supply chain is very important. Commercial printing's greatest manufacturing cost is the paper used (First Research, 2009) and the majority of the environmental impact also comes from paper. The pulp and paper industry accounts for a large percentage of the total energy used, surpassing even the aluminum industry (EIA, 2006). Many paper suppliers have conducted LCAs, but according to one device manufacturer are unwilling to disseminate that proprietary information to their customers (device manufacturer, personal communication, August 10, 2010). In cases where suppliers don't have environmental metrics data, there is concern that the cost to procure such data will be forced upon them (Original Equipment Manufacturer [OEM], personal communication, August 10, 2010). Even if the supplier is willing to supply the LCA practitioner with results data, the lack of a standardized method to account for all attributes would mean that the results could not be compared interchangeably between different suppliers, and assumptions might unknowingly be changed from stage to stage of the LCA. For example, a supplier might account for carbon sequestration of a managed forestry (under PAS 2050), yet the practitioner might not account for carbon release at the end-of-life, since it will not be greater than the amount of CO_2 sequestered (Koehler et al., 2010).

Many LCAs are criticized for uncertainties or inaccuracies surrounding impacts from component manufacture processes, as often the materials used can be identified but not the exact processes used. One of the studies specifically stated that the "greatest source of error is the lack of data on component manufacturing and assemblage of the cartridge" (Four Elements Consulting, 2008). Again, this supports a need for greater dissemination of data upstream in the supply chain.

More open interaction with suppliers can have many environmental and cost-savings benefits. For example, managing reverse flows of materials and packaging can decrease costs and emissions from transportation (Vachon & Klassen, 2006). If the supplier was even willing to link environmental management systems, more accurate environmental data could be linked to internal LCA data sets from suppliers in real time, making data collection more accurate as well as less costly and time inhibitive (Moon, Chung, Eun, & Chung, 2003). For many parts of the printer manufacturing industry, this is not possible as parts are sourced from multiple OEMs at different times (OEM, personal communication, August 10, 2010).

Production

The production and manufacturing stage, while likely having a relatively low impact in the overall LCA, is typically the best populated stage. However, this is not the case in many of these studies. Boguski (2010) went as far as to include overhead operating impacts such as development and marketing staff and travel. This is not typically expected of an LCA but acts as a reminder that the number of impact sources seems almost limitless if some cutoff criteria are not implemented. The two studies which were missing this stage were either focused on end-of-life (Mayers et al., 2005) or it was simply omitted because other aspects were thought to have greater impact (Silva et al., 2006).

Use Phase

In nearly all of the studies examined, the electricity and paper used during the use phase were said to have had the most significant impacts for the imaging device. Due to the importance of the use phase, an increased importance is placed upon user characteristics, habits, and settings. As a result, sustainability services such as print optimization have gained popularity (Rothenberg, 2007). Surprisingly, these services come from companies such as Xerox, which actually relies on paper sales for their profits. This trend started with office equipment but seems to be increasingly more relevant for consumer printers (OEM, personal communication, August 10, 2010). Inclusion of the "Individual Product Comparison" option in HP's carbon calculator also may be a sign of increasing relevance for individual consumers, as it allows for comparison of many of the types of printers this market segment purchases.

Options such as N-up and duplex printing also reduce the impact of print significantly. When using such strategies, it is important to have supporting usage data so that these are accurately accounted for. For example, the level to which duplexing is expected to reduce paper use is debated, since many documents printed are less than one page in length according to Lyra Research (Stobbe, 2007). Xerox estimates that about 20% of documents are printed double-sided (Ebner et al., 2009). Several of the print use patterns and assumptions that have already been described are difficult to estimate since "use patterns are of course highly diverse," and "there are no basic or comprehensively representative use patterns even for one and the same device" (Stobbe, 2007).

End-of-life

End-of-life is another stage of the life cycle where large discrepancies exist in LCA practices, and the printing industry is no exception. A major contributor is that waste management differs by locality, and not all options can be taken into account; therefore analysis for a given product can lead to very different results depending on the type of waste management used (Shen & Patel, 2008). There have been several attempts to determine where such disagreement stems from (Finnveden & Ekyall, 1998; Villanueva & Wenzel, 2007). For the printing industry, recycling rates and the impact of different methods can cause significant differences in outcomes, mainly due to the impact of paper (Counsell & Allwood, 2007). This has led some sectors of the industry to focus on de-inking to increase recyclability (Steward, Tsoi, & Coles, 2008). Ahmadi et al. (2003) reported that 34% more energy is needed in the de-inking process than in the fiber recovery process when exploring end-of-life for toner. When certain unusual woods such as groundwood are used for paper production or when the wood is processed, the paper does not degrade completely—an interesting consideration for carbon impacts. In these instances the paper actually has a negative net effect, as the undegraded wood in landfills sequesters carbon (Boguski, 2010). One viable way to approach such differences is to perform sensitivity analyses.

Remanufacturing and reuse is another area of debate for the printing industry. All of the design tools examined in this work have included some form of remanufacturing in their analyses. Components of printers often have a longer useful life than the printer itself, allowing for reincorporation into machines with newer technology (Kerr & Ryan, 2001). This is more beneficial than reuse of the same machine, as the trends in environmental improvement for consumer electronics such as increased energy efficiency can potentially negate the impact reduction realized from decreased raw materials acquisition due to reuse. It also means that future needs must be predicted to some extent to ensure that components designed for reuse can actually meet new market needs (Östlin, Sundin, & Björkman, 2009). Quality issues from remanufacture of toner cartridges are still under debate and are discussed below.

Inconsistent treatment of end-of-life assumptions can be seen within the studies (see Table 9). Some studies addressed this issue by using sensitivity analyses (e.g., Mayers, France, & Cowell, 2005). Definitions of "remanufactured" and "recycled" are also expected to be highly variable between studies. When looking at the end-of-life assumptions for cartridges, even those that are not remanufactured are recycled to a high degree. This is also the case for the imaging equipment studies, with baseline landfill assumptions of only 1-2%. Region is an important characteristic of these two imaging equipment studies, as they were conducted in the European Union where the WEEE directive for imaging equipment end-of-life is in effect. The paper end-of-life assumptions may indicate that the use of the printed paper plays an important role if it may require long-term archiving. It is interesting to note that the highest recycling rate assumption is seen for packaging paper.

Table 9. End-of-life assumptions for devices and components

Category/ Study #	Purpose	Product or component	Remanu-factured	Recycled	Waste to energy	Land-filled
Cartridges						
[2]	Solid ink vs. LaserJet	LaserJet cartridges	10%	25%	--	65%
[6]	Comparative: Cartridge	HP OEM cartridge	--	19%	--	81%
		Tepro remanufactured cartridge (1)	100%, 3 times	--	--	--
[7]	Comparative: Cartridge	Remanufactured cartridge	84%, 1 time	4%	--	12%
		HP OEM cartridge (2)	--	59%	41%	--
Imaging Equipment						
[4]	Baseline: Various devices	4 disposal scenarios for 3,250 imaging devices weighing 21.6 tonnes total	32%	46%	21%	1%
			32%	46%	--	22%
			32%	41%	--	27%
			32%	--	--	68%
[5]	Baseline: Various devices	V1 & V2: EP copier (3)	1%	58%	39%	2%
		V3 & V4: EP printer (4)	1%	52%	45%	2%
		V5 & V6: IJ MFD (5)	1%	47%	50%	2%
Paper						
[8]	Baseline: Toner	Toner on paper (6)	Archived: 22%	43%	--	35%
[9]	Baseline: Magazine	Printed magazine (7)	Archived: 60%	--	8%	32%
[10]	Packaging printing	Gravure process - Paper	--	80%	--	20%

Category/ Study #	Purpose	Product or component	Remanu-factured	Recycled	Waste to energy	Land-filled
Other						
[8]	Baseline: Toner	Toner waste (10%) (8)	66%	--	--	34%
[10]	Packaging printing	Flexographic process - plate waste (9)	--	--	90%	10%
		Gravure process - metals	--	95%	--	5%
[2]	Comparative: Solid ink vs. LaserJet	Product and component packaging (10)	--	70%	--	30%

Gray shaded cells are populated with data from a sensitivity analysis that was part of this study.

(1) After being reused 3 times, the cartridges are sent to Holland for further reuse or disposal.

(2) Used once then disposed of.

(3) V1: Electrophotographic Copier MFD, monochrome, 26 IPM
V2: Electrophotographic Copier MFD, color, 26 IPM

(4) V3: Electrophotographic Printer SFD, monochrome, 32 IPM
V4: Electrophotographic Printer SFD, color, 32 IPM

(5) V5: Ink Jet Printer MFD, personal (low utilization)
V6: Ink Jet Printer MFD, workgroup (moderate use)

(6) Transfer efficiency of xerographic copying is approximately 90%.

(7) Municipal waste (US).

(8) 10% of toner is cleaned from the belt and collected in the waste bin.

(9) 10% process waste.

(10) 60% of this packaging content was assumed to be recycled and 40% virgin material.

Five of the studies were not included in Table 9 for various reasons including: lack of examples of devices being tested on the tool (study 11), end-of-life assumptions for devices not being included (studies 1, 12, and 14), or the end-of-life stage was outside the study scope (study 13). Study 18 examined the reduction in materials when equipment was remanufactured. However, this study did not provide baseline data with which to compare this reduction. For the Document Centre 265 Digital Copier (modular) and Xerox 5100 Copier (non-modular), landfill waste was reduced 45% and 37%, respectively.

Transportation

With increased globalization, transportation due to outsourcing can contribute to environmental impact. In many cases this is low-hanging fruit, as reduction of transportation also has an associated cost savings. Verso was able to reduce greenhouse gas emissions that contribute to climate change by up to 90% while reducing transport costs by up to 50% (Rowzie, 2008). Seven of the studies did not include data on transportation, most likely because the difficulty of collecting these data outweighed the relatively small impact when compared to the impact of energy use and paper.

Packaging

Inclusion of packaging may seem unimportant, but this inclusion can be significant to the results of some studies, especially when it is included for consumables (Koehler et al., 2010). It seems that the impact of packaging, such as that used to ship the printer itself, is minimal, but that of the packaging used for consumables can add up over the useful life to have a significant impact. Five of the studies omitted packaging data completely in their assessment.

Print Consumables

Transportation and packaging are not the only data that are sometimes omitted. As discussed with the functional unit, paper and print speed are two considerations often necessary for consistent comparability of printer LCA data. Yet paper is sometimes removed from comparative assessments under the assumption that the differences between the products will not have an impact on paper (see Table 10). Figure 3 displays the typical relative impact of different aspects of printers as reported by Ebner et al. (2009). Removing paper from the assessment will make other differences more notable as a percent of total impact. This should only be done for comparative LCAs where the effect of paper is the same for both products; the functional unit includes print volumes and equivalent print rates are being compared. Even in these cases, best practice still would be to display results with and without paper as a sensitivity analysis.

Print speed (PPM) has a direct relationship to energy consumption during the use phase, meaning a higher PPM is correlated to higher use-phase energy demands (Stobbe, 2007). This is important to consider when analyzing data from a study such as Koehler et al. (2009), which examines printers at 50 PPM that are among the most energy-demanding. One factor that has not yet been explored with print speed is to what degree misprints are affected.

Table 10. Study inclusion/exclusion of paper and print speed

Study #	Paper	Print Speed
[1]	IPCC, excludes fiber source	User input
[6]	Included in sensitivity analysis	Constant
[2]	Assumed to be equivalent	Solid ink: 50 PPM; Laser: 51 PPM
[14]	Excluded	Laser: Input; Ink jet: Excluded
[8]	Outside functional unit	Outside function
[12]	Included, adjusted for duplexing	User input
[10]	All substrates included, 8% & 35% paper	Not included
[4]	Outside scope	Outside function
[3]	Omitted to highlight End-of-Life	100 (1) & 65 (2)
[7]	Essential to conclusion	Outside function
[11]	Omitted by designers and users	Omitted
[9]	Included, from Verso LCA	Outside function
[13]	Energy from paper and pulp production relative to user paper input	Based on brand and model selection

(1) Xerox 5100 Copier specifications

(2) Xerox Document Center 265 Digital Copier specifications

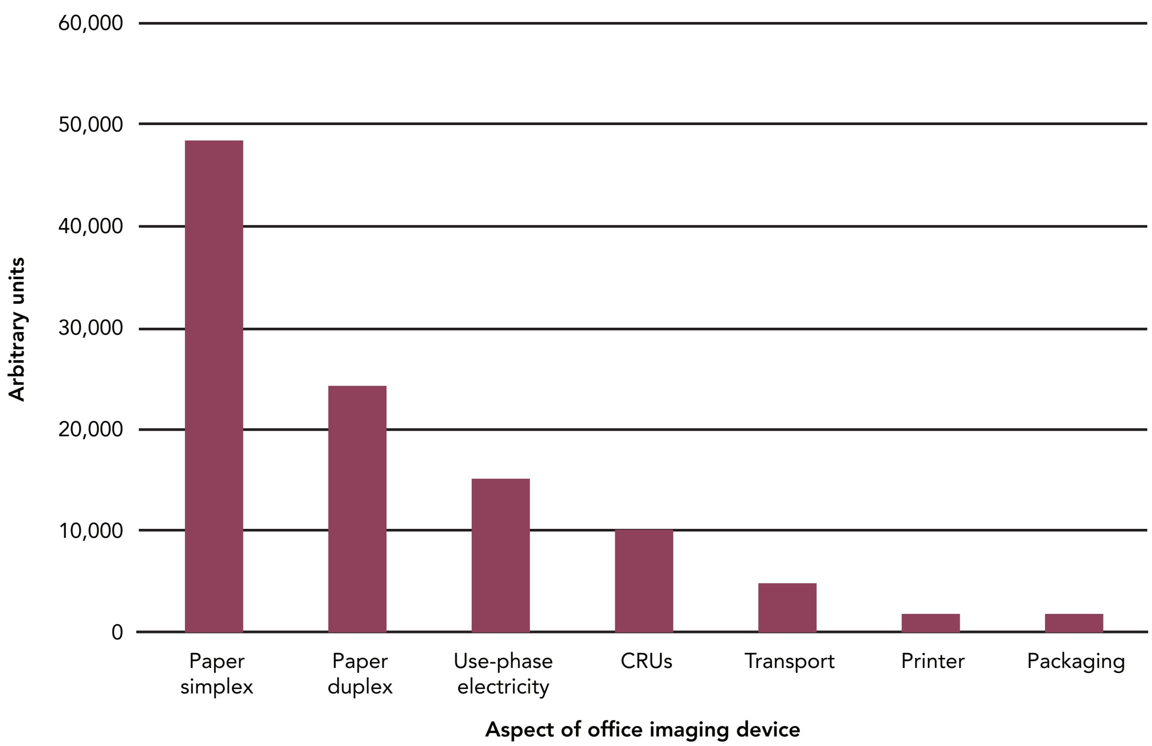

Figure 3. Relative energy and GHG impacts for aspects of office imaging devices

Note: CRUs are "Customer Replaceable Units" such as cartridges (Ebner et al., 2009)

When paper will be included, it is important to specify the type, size, and ink/toner coverage. The standard assumption is that users print on A4 (8.5 in. by 11 in.) paper with an average coverage of 5% monochrome and 20% color, with 5% each for black, magenta, cyan, and yellow. It is also likely that the actual average coverage is higher than this, considering the increase in graphics being printed (Stobbe, 2007).

Cartridges

It is difficult to deal with the life cycle of cartridges without getting into a discussion of their remanufacture. Some companies have made claims in sustainability reports of environmental impact reductions due to their cartridge remanufacture programs. Lexmark recently made claims of an up to 60% carbon footprint decrease for remanufactured cartridges (Lexmark, 2010). Others indicated that remanufactured cartridges in reality have a negative impact due to reduced print quality (Four Elements Consulting, 2008). Despite the fact that the studies are not in agreement, the EuP estimates that only 10% to 15% of cartridges are remanufactured (Stobbe, 2007). In addition, Berglind and Eriksson (2002) concluded that cartridges account for a small fraction of the environmental impact of the printing system, leaving remanufacturing only advantageous under certain circumstances. If this is true, it seems that "neither original nor remanufactured cartridges have a distinct environmental advantage (First Environment, 2004)" (Öko-Institut & Fraunhofer IZM, 2007c, p. 23).

Ink and Toner

Estimates of ink, toner, and cartridge consumption are consistent with yield-testing requirements set forth in ISO/IEC 24712:2007. Much of the chemically active elements of a printing system reside within the toner and ink formulations. It is clearly an important area of focus, primarily due to the fact that these components have the potential to contribute to emissions and airborne particulates, they impact the recyclability of the substrate, and they are derived from process-intensive manufacturing. One of the studies performed an LCA on the toner life cycle including its use and recycling from paper at end-of-life (Ahmadi et al., 2003). Other studies focused on the print consumables' packaging, reducing the environmental impact through safer adhesives, improving materials selection, and increasing the recyclability (Loh, Canonico, Degher, & Moore, 2004). In commercial printing there is a greater focus on inks and solvents due to their volatility. Volatile Organic Compounds (VOCs) and their air emissions have become a major concern for commercial print shops in relation to employee health. This issue exists with office printers on a smaller scale, as they also are a source of particulate matter, ozone, and VOCs (Morawska et al., 2009). In one study, total VOCs ranged from 0.2µg /copy for an ink jet printer to 7.0µg /copy for a LaserJet (Lee, Lam, & Fai, 2001).

Life Cycle Inventory

Life cycle inventory (LCI) analysis defines and quantifies the flow of materials and energy into, through, and out of a product system (ISO 14040:2006). Many of the life cycle inventory issues have been discussed in the scope analysis. For example, the selection of the system boundaries dictates the elements and data to be included and modeled in the analysis. Data requirements and availability issues could arguably be included in all sections. In this section, the issues related to data will mainly revolve around identifying uncertainty and some of the ways practitioners have tried to address these issues.

By this phase of the LCA study, the practitioner has determined what will and will not be included, but there is still an issue of how to allocate the impact data to the inventory data. Much like dilemmas with life cycle costing methods, there are processes that benefit multiple stages of the life cycle and/or multiple products, and these burdens must be properly allocated. For example, if paper is recycled at end-of-life, what share of the original burden of materials acquisition should be allocated to the original LCA and which should be allocated to the next function of that paper? This allocation dilemma is not specific to the printing industry, and practitioners should attempt to follow standards such as ISO wherever possible. When not possible, the practitioner should use sensitivity analysis to determine how important the allocation is to the results or state that it is unknown and use the most easily justified allocation method (Ekvall & Finnveden, 2001).

Two sources of preventable data quality issues typically occur: those due to data gaps and those due to use of proxy or generic data (Reap, Roman, Duncan, & Bras, 2008b). Many of the studies in this work included sensitivity analyses that used different assumptions for uncertain parameters such as recycling rates. Data quality and uncertainty issues are not unique to the printing industry and represent a major issue that LCA has yet to completely overcome.

A substantial barrier to adoption of LCA metrics has been the cost of collecting necessary data (packaging label printer, personal communication, August 10, 2010). When an LCA is performed, practitioners often note the difficulty of obtaining accurate data. In fact, five studies specifically note that this difficulty impacted their results.

Data Sources

It is worth noting the commonly used databases and methodologies, as well as the standards and certifications upon which industry LCAs and decision tools are based. Figure 4 shows the most commonly cited certifications and standards with the number of studies that referenced them. (Appendix B has two tables: one showing which studies cited which resource in Figure 4, and the other listing literature that was cited by the studies for data.)

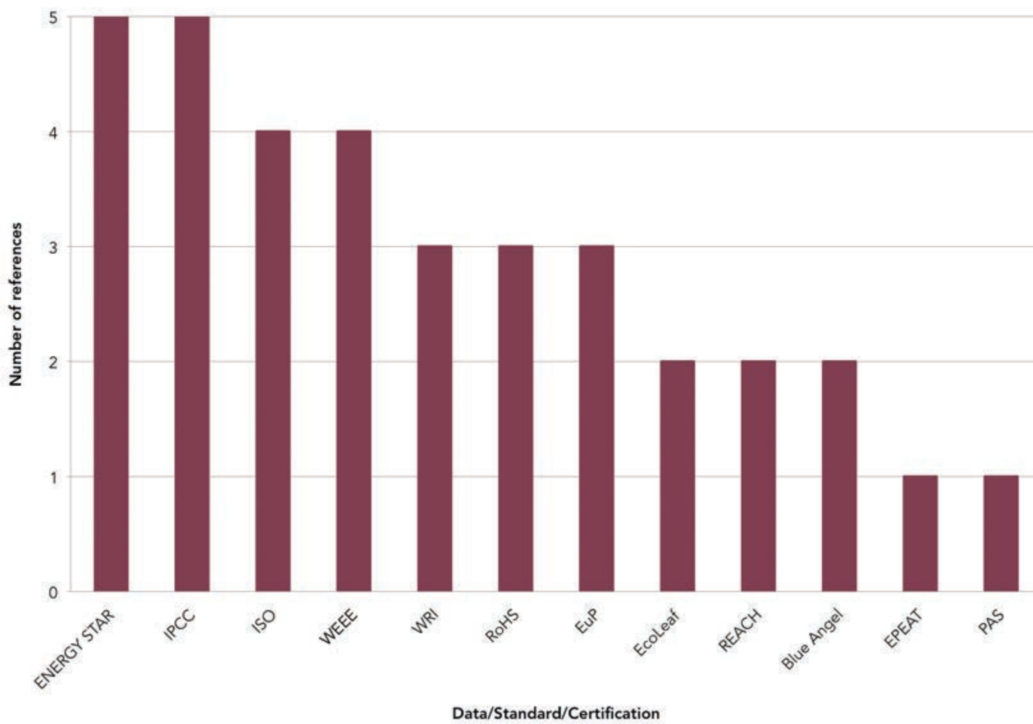

Figure 4. Referenced data, standards, and certification sources within studies

The ENERGY STAR standard and database are used frequently in these studies. The standard set forth in Typical Electricity Consumption (TEC) is necessary because of the complexity of energy consumption with varied rates and modes. This standard also is specific to imaging equipment. Many companies seek TEC certification for their products, so products being studied by the LCA may already have had TEC determined. The consistency and high usage rate also have helped to make the associated ENERGY STAR database very useful. The database helps to identify trends and baselines for studies such as the EuP, and it provides data on competitors' products for inclusion in tools like HP's Carbon Footprint Calculator. Energy is an important component of use-stage environmental impact and this information is therefore very useful.

IPCC is also cited frequently for the standard treatment of Global Warming Potentials (GWP) over a period of time such as 100 years (IPCC, 2006). All but two of the studies determined impacts for GWP, as this is one of the few impact categories with a clear set of guidelines. It was surprising, however, that PAS 2050 was not cited more frequently, since it is a very specific set of guidelines used to calculate carbon footprint. The relatively low mention of EPEAT also was somewhat surprising given its relevance to consumer electronics. This may change, as upcoming standards for imaging equipment (IEEE 1680.2) are expected for November 2010. This new standard will likely include criteria for consumables (i.e., paper and ink) and indoor air quality in addition to the former 1680 criteria. Likewise, the EuP will probably be used even more as an industry average indicator in the future considering the large amount of data it analyzed.

The National Council for Air and Stream Improvement (NCASI) was not referenced for paper impact calculations in any of the studies; however, their recent Forest Industry Carbon Assessment Tool (FICAT) is likely to be a useful resource. Lastly, certifications such as EcoLeaf (Japan Environmental Management Association for Industry, 2002) in Japan and RoHS/REACH/WEEE in Europe obtain recognition from companies that operate in their regions but are less likely to be as useful for other regions. It also is important to note that these regulatory certifications are already being surpassed. Design tools may still use them as starting points, but LCAs are unlikely to incorporate them quantitatively.

Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) converts the inventory data collected during the inventory analysis into environmental impact estimates using a two-step process of classification and characterization (ISO 14040:2006). This is a complex and somewhat subjective process, which is the reason such care has been taken to identify where data has come from. "It is clear that this is a complex process, thus the impact component of the LCA has always been very subjective" (Ahmadi et al. 2003). The solution has been to utilize impact assessment software which adheres to published methods and often includes multiple databases. The discussion of data in this section will focus mainly on specific data sets, data quality, and the pros and cons of alternative methodologies.

Methodologies

There are already reviews and evaluations of different published methodology tools available which are not specific to the printing industry (Pennington, Norris, Hoagland, & Bare, 2000). When life cycle inventory data representing raw materials and processes are converted into environmental impact categories, the results are considered midpoints, such as energy use or CO_2e (Bare, Hofstetter, Pennington, & Udo de Haes, 2000). Endpoints require an additional step where impact categories are aggregated through weighting factors (examples: Eco-Indicator 99, EPS 2000, IMPACT 2002, EDIP, see Bengtsson & Steen, 2000). The further a study gets toward an endpoint, the more influence that methodology has. Some studies choose to present results as endpoints, and others just as inventories of impacts, such as the 2003 study by Ahmadi et al.

Impact Categories

Life cycle publications that intended to differentiate products based on their environmental impacts tend to focus on three or four main impacts instead of presenting an end-result weighted score or a more complete set of impacts (Reap et al., 2008b). This can be seen with many of the LCAs meant for external audiences reviewed in this work. Practitioners selectively limit the number of impact categories so as to avoid overwhelming the reader with information that is relatively less important. Even though Koehler et al. (2010) were using a software tool (SimaPro 7) which, by default, includes multiple impact categories, the researchers decided to limit the results to GHGs, energy use, and solid waste. The danger here is that impact categories have to be normalized to determine significance relative to one another. An impact on human toxicity may be very small and an impact on GHG may be very large, but the importance of human toxicity might be such that this impact is actually more important than the GHG impact. Studies performed in academia are more likely to include all impact category results, even if they are very small or not relevant. Figure 5 shows impact categories by study audience based on data shown in Appendix B.

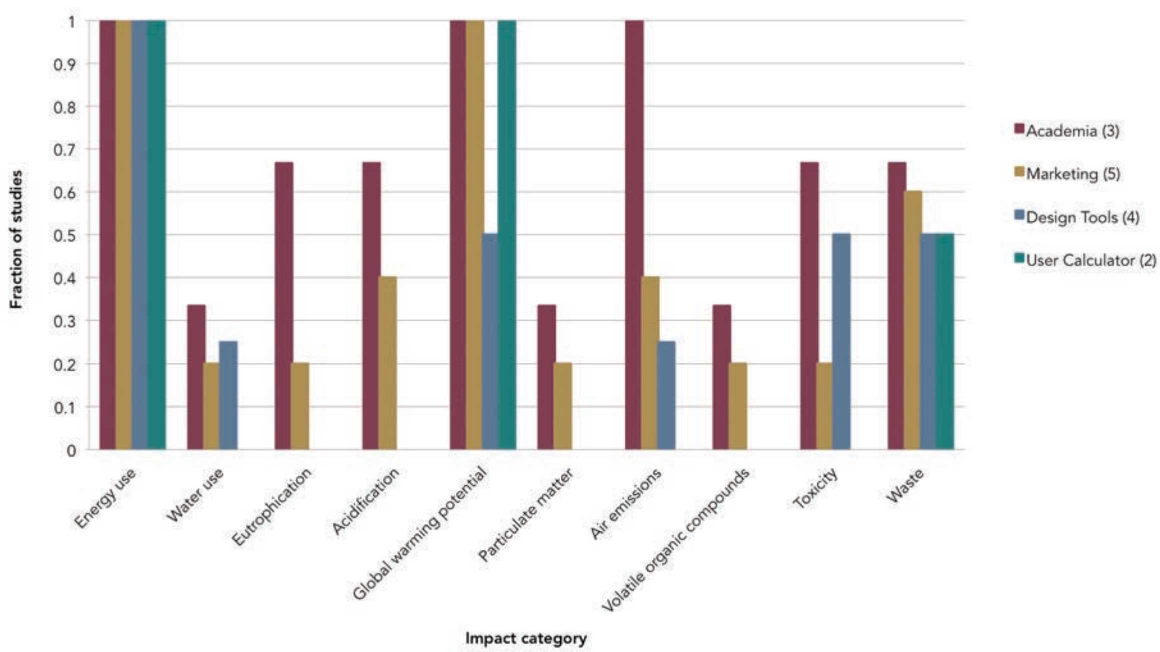

Figure 5. Study inclusion or exclusion of impact categories based on intended audience

Global warming was the leading impact category of the studies (excluding energy use). This is likely due to the importance placed on CO_2 emissions in recent years. There is also a universally accepted standard in place: IPCC GWP. Other emissions have far less emphasis in consumer markets; however, VOCs are very important to the commercial printing industry, and there are some standards for determining emission such as ECMA-328 (ECMA International, 2009).

Several reasons for omitting impact categories include a lack of standards (Ekvall, 1999), lack of data, the belief that the category is irrelevant, or lack of consideration within the methodology being used (Reap et al., 2008b). Several standards, unlike GHG, lack "harmonized" and consistent methodologies for terrestrial and aquatic toxicology in LCA (Pennington et al., 2000), and incomplete databases are inhibitive and have caused a concerning gap (Shen & Patel, 2008).

Impacts of toxicity and human health typically get less attention, even though this would seem to be a priority impact (Reap et al., 2008b). This is partially due to the regulations already in place for chemicals and outputs that would be a threat to human health. Resource depletion does not receive much attention in the studies, with the exception of energy use. Energy use is typically treated as a midpoint rather than an impact category, as it contributes to other impacts such as GWP. It was assessed here as an impact category because many studies do not differentiate between the end points to which energy use is allocated. Again, the impact with a standardized data collection and allocation methodology—in this case energy use—is presented more frequently. The inclusion of energy use could also be an effect of its more immediate economic implications.

Waste receives a lot of attention considering the high level of uncertainty in end-of-life data. This is consistent with LCAs outside of the printing industry. Ekvall (1999) presents some methodologies specific to paper end-of-life and recycling.

Breadth and Depth of Assessment

In an attempt to summarize much of what has been reported up to this point, a breadth and depth assessment process was developed. First, it was of interest to determine if there were differences between the study context with respect to breadth and depth. The dominate study audience was selected to represent this context for comparison. In order to assess the breadth of the assessment, the stage data evaluations from Table 8 were averaged across context groups. Similarly, to assess depth the impact category inclusion data from Figure 5 were averaged for each of context groups.

For impact categories, a score of 1 - 4 was assigned for the number of studies including each category, and then these scores were averaged. For stage data, the grades from Table 8 were given numerical scores ranging from A = 4 to D = 1. Grades of E were omitted from the average, as these were excluded from the study for specific reasons rather than data collection difficulties. Impact categories could be skewed; however, all context groups (with the exception of academia) had categories that were included and excluded in all studies within the group. This can be seen in greater detail in Figure 6.

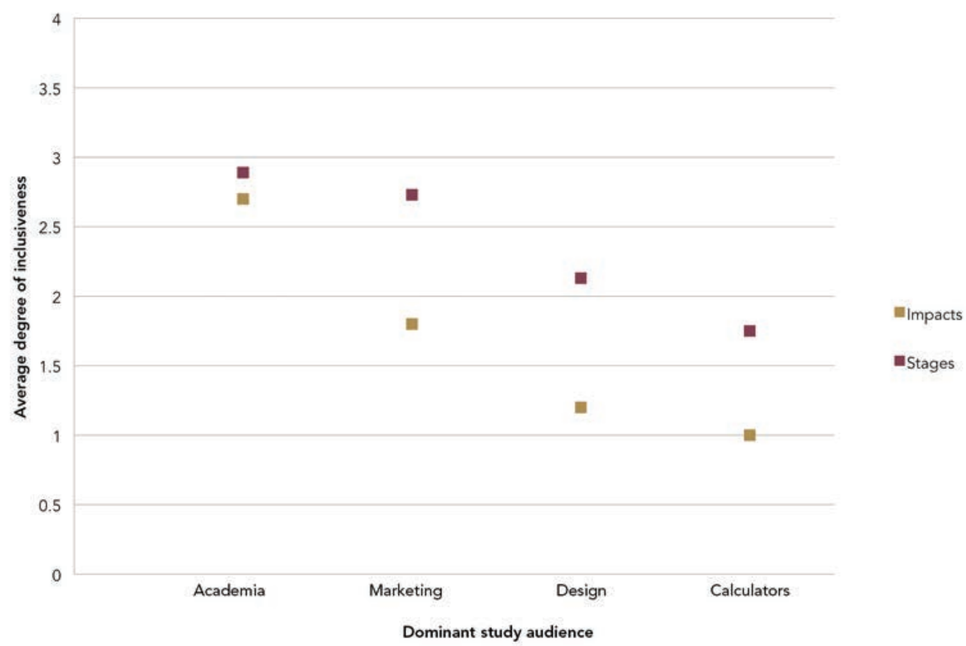

Figure 6. Breadth and depth of assessments in studies

Academia was the most inclusive of both stage data and impact categories. This is not surprising given the focus on establishing baseline data and presenting replicable results. Studies performed for external marketing purposes had the same level of stage data but ranged from 2.3 to 3 on a 4-point scale. It was interesting that studies for external marketing were more inclusive than those for internal design. This may suggest that internal design tools have been streamlined beyond the point desired for external communications but not to the point where they inhibit good decision-making. Not surprising is that impacts typically included for external marketing—carbon emissions, and waste—are typically included in customer calculators. The use stage is explored to the greatest extent in both of these categories of study, but there do not seem to be any other stage data similarities.

Reporting and Critical Review

Performing LCAs internally has the advantage of keeping data proprietary (print shop, personal communications, August 10, 2010). Several major companies have performed LCAs and published improvement results for marketing purposes (Lexmark, 2010) or within their sustainability reports (Ricoh Group, 2009; Canon Inc., 2010). However, the actual quantitative results and the complete assessment have not been published, ensuring that proprietary information will not be disclosed.

Recognizing the desire to retain proprietary information but also balancing the need to keep transparency and accountability has led to ISO's requirements on reporting and critical external review (ISO 14040:2006). This is important considering the limited data disseminated in many LCA reports to protect industry proprietary data. Having a review performed within academia or by an outside consultant can help reassure consumers that data were accurately analyzed. These external partnerships with consultants and academia can have other added benefits, especially for smaller-scale enterprises that lack competencies or scale. Not all LCA reports go through this process however, and as mentioned previously, often a company will report results in a news release or sustainability report.

Conclusions and Further Research

A great deal of activity is occurring in environmental impact assessment within the printing industry. It is clear that a great deal of effort and expense has been put into these assessments. While each of these analyses has served specific purposes, the printing industry has expressed the need to be able to make meaningful comparisons across studies. The analysis performed in this work has not only confirmed the inability to make cross-comparisons across studies, but has also identified sources of discrepancies and variability.

Some of the important observations made in this work, as well as implications for future work, are summarized below:

- Both design decision tools and full LCA have a role in a company's environmental sustainability program.
- An approach to standardization needs to include the standardization of measurement methods. This is evident from the prevalent use of GWP 100-years and ENERGY STAR energy consumption standards cited. By following this approach for other categories, more cross-study comparisons will be facilitated.
- Like most LCAs, those performed in the printing industry still lack reliable data for the early life cycle and end-of-life of paper since these are difficult to agree on. Some uncertainty issues can be solved by increasing data and data transparency through the inclusion of metadata or reviews.
- Products have diverse functional values beyond simple document production, and these need to be considered in addition to LCA results when making design decisions. Standardization of the functional unit and its included assumptions has a high potential to increase quantitative comparability across studies. At the same time, caution must be taken not to use "paper" to define the imaging device's function, allowing for the inclusion of alternative media in the comparison.
- Assumptions that are not standardized lead to difficulties in comparisons between studies. Some of the most significant assumptions are those on usage

behaviors. One approach has been to limit the inclusion of use-phase impacts like paper. This fails to account for any differences that may occur during this phase, however, which may be very significant. Consumer behavior has potential to be the greatest environmental impact reducer (i.e., by reducing misprints or the necessity of printing altogether). The only way to quantify these differences is to gather extensive usage data. A sensitivity analysis should also be included with these behavior data as they are highly variable. Non-LCA decision tools have an advantage in this respect as many of them can simply input qualitative data.

- Consumables should continue to be examined closely. Ink and toner advancements and alternatives have potential to make improvements in less popular impact categories. One such example is the use of soy-based inks (Tolle, Evers, Vigon, & Sheehan, 2000). The key to reducing the impact of paper will be wasting less of it and making it more recyclable.

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Appendix A: Life Cycle Stage Data

Academic Studies to Establish Baseline Data		
Life Cycle Stage	[5] Stobbe 2007	[4] Mayers 2005
Raw Materials Acquisition	*Excluded*	Reuse considered
Production	Based on materials, omit assembly	*Excluded*
Transportation	Based on mass and volume	*Excluded*
Use	With and without paper	*Excluded*
End-of-life	Does not include reuse, leasing, etc.	Focus of study. Reuse included.
Packaging	Included in Misc. when available	Included in collection

Cartridge Remanufacture			
Life Cycle Stage	[6] Berglind 2002	[7] Four Elements 2008	
Raw Materials Acquisition	Materials production from various sources	99.5% of materials listed	25% of materials recycled
Production	Assembly and restoration/ refilling	No supply chain data. Proxies to cartridge parts were used for injection molding, steel, and aluminum processes.	
Transportation	Distance estimated for all phases	Distribution only, 1,500 miles for R10A, 5,150 miles for HP10A.	
Use	46.7 kg paper, 63 kWh energy, and 373g toner	426 Watts, 24ppm, 6,000 pages 101 pages (†)	426 Watts, 24ppm, 5877 pages 114 pages(†)
End-of-life	Compares two alternatives, but otherwise the same	82% Landfill 18% Weight-to-Energy	
Packaging	European database for corrugated board (‡)	28g polyethylene, 355g corrugated cardboard, 142g pulp end caps.	

(†) Printed pages necessary to obtain 100 acceptable quality prints (Quality Logic, 2007)
(‡) European Federation of Corrugated Board Manufacturers [FEFCO], Groupment Ondulé,, & Kraft Institute, 2000.

Comparative LCA		
Life Cycle Stage	[10] Veith 2008	[2] Koehler 2010
Raw Materials Acquisition	*Excluded*	*Excluded*
Production	Manufacture of the photopolymer plates	Manufacture of printer and consumables
Transportation	Excluded	Transport of consumables
Use	Imaging, plate mounting, and printing	Use of the device
End-of-life	Process wastes included	Service activities and device end-of-life excluded. Cartridges: 10% remanufactured & 25% recycled.
Packaging	*Excluded*	Packaging of consumables: 60% recycled. End-of-life: 70% recycled.

Tools for Design/Decision			
Life Cycle Stage	[11] Silva 2006	[12] Ebner 2009	[1] Ord 2009
Raw Materials Acquisition	Material mass, and toxicity (Eco-Indicator 99)†	Material reuse	32 material masses (Ecoinvent database)‡
Production	Excluded	Materials toxicity	IPCC 2007
Transportation	Excluded	Excluded	Up to assembly
Use	Average power consumption. CO_2 emissions during use.	Energy and air quality	Based on energy estimator
End-of-life	Functional life, upgrade option and recyclability.	Percent of mass recyclable	Expected life is input. Ease of recycling.
Packaging	Material and quantity	Hulk packaging mass	Excluded

† Goedkoop & Spriensma, 2000

‡ Swiss Center for Life Cycle Studies, 2007

Consumer Calculators		
Life Cycle Stage	[13] HP 2009†	[14] Xerox 2008
Raw Materials Acquisition	*Excluded*	Energy & GHG results by stage EuP Data
Production	Paper & pulp	Energy & GHG results by stage
Transportation	*Excluded*	*Excluded*
Use	Energy (TEC) Paper (Ecoinvent)‡	Energy & GHG results by stage
End-of-life	*Excluded*	Solid waste results for each stage
Packaging	*Excluded*	Consumables packaging

† Excluded stages may contribute CO_2e impacts based on the Ecoinvent database, but these aspects of the scope is not addressed in the study.

‡ Swiss Center for Life Cycle Studies, 2007

Printers/Printing Processes			
Life Cycle Stage	[3] Kerr 2001	[10] Boguski 2009	[8] Ahmadi 2003
Raw Materials Acquisition	Measured materials consumption avoided	Primary data forestry/wood harvest from paper supplier.	Carbon black, magnetite & resin components
Production	Energy saving due to remanufacture	Primary data from pulp and paper mill operations, printer operations, content development and even advertising activities.	Toner manufacturing from materials
Transportation	*Excluded*	Domestic and international distribution (USPS data †)	Raw materials to toner manufacturer, toner to customer, toner waste recycle
Use	*Excluded*	Consumer use/reuse	Consumer use
End-of-life	Measured avoided waste disposal	Domestic and international practices weighted	Toner recycle, de-inking of paper, toner on paper to landfill
Packaging	*Excluded*	Pallets and packaging	Included in toner manufacturing

† SLS Consulting, 2008

Appendix B: Referenced Certifications and Standards

Data/Standard	Studies
ENERGY STAR	Stobbe 2007 Ebner 2009 Koehler 2010 HP 2009 Xerox 2008
MEEuP EcoReport	Stobbe 2007
EcoBilan	Mayers 2005
American Forest & Paper Association	Ahmadi 2003
EcoInvent	Ord 2009
WRI	Ord 2009 HP 2009
IPCC	Ord 2009 Mayers 2005 Boguski 2009
SimaPro 7	Koehler 2010 Veith 2008
LCAiT	Berglind 2002

Standard/Certification	Number of studies referenced
ENERGY STAR	5
IPCC	5
ISO	4
WEEE	4
WRI	3
RoHS	3
EcoLeaf	2
EuP	3
REACH	2
Blue Angel	2
EPEAT	1
PNAS	1

Appendix C: Impact Categories and Data Used in Studies

	Academia Studies*				
	Impact Category	[5] Stobbe 2007	[4] Mayers 2005	[8] Ahmadi 2003	[6] Berglind 2002
Resources	Energy	ENERGY STAR database (US Environmental Protection Agency [EPA], 2010)	Non-renewable resources: Finnveden, 1994	Energy use emissions calculated from EDF (1995) Fossil Fuel	Calculated based on usages
	Water	MEEuP EcoReport†	--	Wastewater	--
Emissions	Eutrophication	MEEuP EcoReport†	Centre for Environmental Studies (2001)	--	--
	Acidification (SO_2e)	MEEuP EcoReport †	Ecobilan Group (1998)	SO_2 and NOx	--
Air Emissions	Global Warming Potential	MEEuP EcoReport † 100 years	IPCC (1996) and Ecobilan (1998) 20, 100 & 500 year cases	Electricity CO_2	GWP 100-years
	Particulate Matter, dust	MEEuP EcoReport †	--	Particulates	--
	Persistent Organic Pollutants (POP), Ozone Depletion & Photochemical Oxidant Formation	POP & ozone depletion: MEEuP EcoReport†	Photochemical oxidant formation & ozone depletion: Ecobilan (1998)	--	NOx – LCAiT software
	Volatile Organic Compounds	MEEuP EcoReport†	--	VOCs (Jiménez-Gonzalez, Kim & Overcash, 2000)	--
Toxicity	Polycyclic Aromatic Hydrocarbons, Heavy Metals and other	MEEuP EcoReport†	Jolliet & Crettaz 1997; Jolliet 1994, 1996; Guinée et al. 1996	--	--
Waste	Waste (non-hazardous/land fill)	MEEuP EcoReport†	--	66% toner recovered (Azar, 2001) 43% paper recycled (American Forest & Paper Association, 2009)	Waste Generation – LCAiT software
	Waste (hazardous/ incinerated)	MEEuP EcoReport†	--	--	--

* Study 5 (Silva, 2006) is not included here, as it does not attribute any data to its midpoints

† Kemna, Elburg, Li, & Holsteijn, 2005

	Design Decision Tool				
	Impact Category	[1] Ord 2009	[12] Ebner 2009	[11] Silva 2006	[3] Kerr 2001
Resources	Energy	Ecoinvent database. Emissions factors from World Resources Institute [WRI] (2004)	ENERGY STAR TEC-based internal estimates (EPA, 2007)	Average power consumption	Not Quantified
	Water	--	--	--	Not Quantified
Emissions	Eutrophication	--	--	--	--
	Acidification (SO_2e)	--	--	--	--
Air Emissions	Global Warming Potential 100 Years	IPCC (1996) used to convert to CO_2e	--	--	Not Quantified
	Particulate Matter, dust	--	--	--	--
	Persistent Organic Pollutants (POP), Ozone Depletion & Photochemical Oxidant Formation	--	Based on Blue Angel (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2010)	--	--
	Volatile Organic Compounds	--	Based on RoHS (European Union [EU], 2003b) & REACH (EU, 2006)	--	--
Toxicity	Polycyclic Aromatic Hydrocarbons, Heavy Metals and other	--	--	RoHS (EU, 2003b)	--
Waste	Waste (non-hazardous/ land fill)	--	--	Recyclability and disposal options	Not Quantified
	Waste (hazardous/ incinerated)	--	--	--	--

	External Communications (Marketing)				
	Impact Category	[9] Boguski 2009	[2] Koehler 2010	[7] Four Elements 2008	[10] Veith 2008
Resources	Energy	Fuel and electricity for a variety of locations and transportations	ENERGY STAR TEC (EPA, 2007)	EcoIndicator 99 (Goedkoop et al., 2000) and inventory results	SimaPro 7 (Product Ecology Consultants [PRé], 2006)
	Water				
Emissions	Eutrophication			IMPACT 2002 (Humbert, Margni, & Jolliet, 2005)	
	Acidification (SO_2e)			IMPACT 2002 (Humbert et al., 2005)	
Air Emissions	Global Warming Potential	IPCC (1996)	SimaPro 7 (PRé, 2006) "industry average" data used when direct manufacturing data not available	IPCC (1996)	IPCC (1996)
	Particulate Matter, dust				
	Ozone, Persistent Organic Pollutants, Photochemical Smog			Photochemical Smog Potential (Centre for Environmental Studies, 2001)	
	Volatile Organic Compounds				
Toxicity	Polycyclic Aromatic Hydrocarbons, Heavy Metals and other			Vinyl Chloride, IMPACT 2002 (Humbert et al., 2005)	
Waste	Waste (non-hazardous/land fill)				
	Waste (hazardous/incinerated)		Post consumer waste generation	Inventory result	

	External Calculators		
	Impact Category	[13] HP 2009	[14] Xerox 2008
Resources	Energy	ENERGY STAR TEC (EPA, 2007)	ENERGY STAR (EPA, 2008)
	Water	--	--
Emissions	Eutrophication	--	--
	Acidification (SO_2e)	--	--
Air Emissions	Global Warming Potential	WRI (2004) 100 year GWP	EuP (Stobbe, 2007), International Energy Agency (Bosi, 2000), U.S. LCI database (National Renewable Energy Laboratory, 2004)
	Particulate Matter, dust	--	--
	Persistent Organic Pollutants, Ozone Depletion and Photochemical Smog	--	--
	Volatile Organic Compounds	--	--
Toxicity	Polycyclic Aromatic Hydrocarbons, Heavy Metals and other	--	--
Waste	Waste (non-hazardous/land fill)	--	Based on primary data or industry average
	Waste (hazardous/incinerated)	--	--

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