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Life Cycle Assessment in the Print Industry

A Critical Review

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Summary

This article compares life cycle assessment studies performed on imaging equipment for the consumer market in order to identify common practices, limitations, areas for improvement, and opportunities for standardization. The analysis suggests that comparisons across studies are significantly hampered by variability in scope, transparency, data sources, and assumptions; it identifies sources of discrepancy and variability. Of particular concern to printing devices was the definition of a functional unit, which can vary significantly depending on the capabilities and use patterns of a printer. Standardization of the functional unit and related assumptions has a high potential to increase quantitative comparability across studies. At the same time, standardizing the functional unit by paper usage excludes the possibility of comparison to alternative communication media.

Introduction

Conducting life cycle assessments (LCAs) or similar assessments, such as carbon footprint analysis, has become increasingly prevalent as a means to convey environmental impacts to a range of stakeholders. While widely used, the expansive data requirements and high associated costs of LCAs remain problematic (Reap et al. 2008a). To deal with these issues, many decision tools and assessments have streamlined data requirements, limiting scope and impact categories to those hot spots with the greatest influence on the final result. While this streamlining successfully reduces the data collection requirements, it also decreases compatibility and comparability across LCA applications. In addition, many of the methods for quantifying these impacts are based on varied assumptions, making comparisons across LCA studies difficult.

The printing industry faces these (and other) challenges in its attempt to broadly measure and compare environmental impacts. Printing has become a ubiquitous part of our lives, ranging from the printing of personal documents and family photos, to the documents we use in business communication, to the mass production of advertisements, magazines, and packaging. Given the pervasiveness of print, many organizations are interested in the environmental impacts associated with its life cycle. Considered in their entirety, these impacts are significant. For example, in 2006 the U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey ranked the paper industry (North American Industry Classification System [NAICS] Code 322) as the third largest industrial consumer of energy (EIA 2006). A similar finding was reported by the Organisation for Economic Co-operation and Development's (OECD) International Energy Agency (IEA), which collectively ranked the pulp, paper, and printing industry as the fourth largest industrial consumer of energy (OECD/IEA 2007). Given these impacts, a clearer understanding of the life cycle environmental impacts of printing is naturally of interest to manufacturers, consumers, policy makers, and various other stakeholders.

There are a number of challenges for practitioners conducting LCAs of the printing industry, several of which are shared

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by the broader consumer electronics industry. Fast-paced technological advances shorten product lifetimes, quickly making technology-specific data obsolete (Anders and Andersen 2010). These technology-specific data are already difficult to collect because materials and processes differ greatly between products, requiring extensive knowledge and communication across international supply chains. Furthermore, given the impacts discussed above, manufacturers within these supply chains are reluctant to share proprietary data, making it difficult to conduct LCAs without help from partner manufacturers. The printing industry has the added challenge of accounting for consumables, such as paper and marking materials (e.g., toner and ink), as well as the effects of consumer behavior, which ultimately impact material consumption rates.

While there is strong interest within the printing industry to better understand its environmental impacts, a recent study suggested that the printing industry is following a somewhat insular approach to environmental impact assessment, creating the potential for inconsistency across studies (Gambeta et al. 2010). To better understand how this potential is being realized, this article provides a critical review of publicly available LCA reports within the printing industry. The objective of this work is to explore differences and similarities of environmental impact studies within the printing industry in order to

- compare life cycle stages and impact categories;
- understand the context, scope, and assumptions;
- compare the data quality;
- determine how to enable better comparisons of future environmental impact studies; and
- establish a baseline for continued review of environmental impact studies.

Differences and similarities are identified among these LCA studies based on the International Organization for Standardization (ISO) 14040 life cycle assessment framework. Twelve LCA studies were identified for inclusion in this review. The remainder of this article will describe the literature collection methodology and briefly summarize each LCA study. This is followed by a description of the analysis methodology and the identification of common practices, major differences, and limitations, with particular attention paid to assumptions and boundaries that influence key outcomes. The article concludes with areas for improvement in assessing environmental impacts within the printing industry, as well as opportunities for and problems with standardization.

Literature Review

Scope

The printing industry encompasses a range of activities similar to any product life cycle, including content creation, content production (printing), document distribution, document use, and document end-of-life disposal. A document can be a single printed page, bound report, photo book, magazine, or even printed packaging materials. However, in this particular review we selected studies that dealt directly with imaging equipment and their associated consumables. The term *imaging equipment* is defined in the energy using products (EuP) preparatory studies as a "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, 12).

There were two main reasons for this selection. First, companies that manufacture imaging equipment have been proactively taking steps to minimize their environmental impacts and have independently conducted several studies of their products to promote this fact (see the following section for details). Second, there is increasing scrutiny of this class of product. For example, the Institute of Electrical and Electronics Engineers (IEEE) P1680.2 Standard for Environmental Assessment of Imaging Equipment, currently under development, will provide a set of performance criteria to be used in tools intended to help inform purchasers of the environmental impact of electronic products (IEEE 2010) (see, e.g., the Electronic Product Environmental Assessment Tool).

We decided not to focus on studies of the pulp and paper industry. Paper is clearly an important contributor to the life cycle impacts of printing, but discussion of paper's impact is only considered to the extent that it is a factor in our sample of equipment studies. For the interested reader, Dias and colleagues (2007) and the Food and Agriculture Organization of the United Nations (FAO 2010) provide excellent reviews of paper and pulp industry LCAs.

Another limitation on scope was based on the intended market segment of the imaging equipment. The printing market can be broadly classified as either consumer or commercial. The consumer market can be characterized as home and office use, where the printed output supports the users' activities. In contrast, the commercial market is characterized by the fact that revenue is largely and directly dependent on the printed output of the imaging equipment. The quantity being printed has been used as a way to distinguish between the consumer and commercial markets, with more than 100 pages per day being considered commercial (U.S. EPA 2007). For our analysis we focused on the consumer market.

Study Sample Selection

The initial search process consisted of an exhaustive review of secondary source materials; a list was created of all the studies we could find that fit the broadest scope of LCAs of the printing industry. Because we were focusing on process rather than quantitative results, the literature reviewed was not limited to LCAs, but included assessments that took a life cycle approach and considered multiple portions of the product life cycle. Thus studies included both the device and marking consumables, such as print cartridges. There were some studies we found references to but were unable to obtain because they were proprietary. An attempt was made to not limit studies to any particular region of the world. This process resulted in a list of approximately 40 references and included studies that ranged from personal printing to the printing of magazines and packaging.

The list was then reviewed by industry experts to ensure that no major studies had been omitted. After adding studies suggested by our reviewers, studies were eliminated based on the criteria described in the section above on scope. Table 1 provides a brief overview of each study, including the context (e.g., study goals, practitioner affiliations, and products examined), as context heavily influences uncertainty tolerances, interpretation, the frame boundary, and assumption decisions (Wenzel 1998).

We categorized the final set of studies in two different ways. The first was the intended purpose of the study, which included the following categories: supporting an external marketing message (External Marketing), supporting design and business decisions (Design), informing policy (Policy), and calculators to inform customers (Calculators). Policy is the most broadly defined category and includes analyzing policy, setting baselines, identifying hot spots for policy development, and comparing of alternative technologies rather than specific products. For the purposes of analysis, each study was assigned to a primary purpose category, though some studies could clearly serve multiple purposes. The second dimension was the practitioner (i.e., LCA primary author) type, which included the manufacturer of the device, third-party hired consultant, and academic/independent researcher. These purpose and practitioner categories are not exclusive, but were developed based on a weight-of-evidence approach.

External Marketing

[1] Koehler, D., W. Latko, and A. Stocum. 2010. The multifunctional Xerox solid ink LCA white paper serves as a quick overview of a Xerox comparison study performed on a color solid ink multifunctional printer and a comparable color laser multifunctional printer.

[2] Berglind, J. and H. Eriksson. 2002. One of the first LCAs to assess the environmental impact of cartridge remanufacture and reuse for laser printers. In this study the environmental impact of an original Hewlett Packard (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.

[3] Four Elements Consulting 2008. Four Elements Consulting revisited a 2004 First Environment LCA study comparing 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. This study examined differences in print quality page acceptance between original and remanufactured toner cartridges.

Design Decision Tools

[4] Ord, J., S. Canonico, T. Strecker, and E. Chappell. 2009. HP's Imaging and Printing Group (IPG) reports on the development process undertaken to establish the initial internal metrics that will guide design, chart progress, and set environmental goals for products.

[5] Ebner, F., S. Chang, J. Knapp, V. Deyoung, and W. Latko. 2009. Xerox's Green Scorecard is neither a design tool nor a substitute for an 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.

[6] Silva, N. D., I. S. Jawahir, O. Dillion, and M. Russell. 2006. This study 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/remanufacturability. The study compares how design practitioners and consumers place different levels of importance on these elements.

[7] Kerr, W. and C. Ryan. 2001. This study investigates whether remanufacturing at Fuji Xerox 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, it adhered to LCA processes and delineations.

Policy

[8] Ahmadi, A., B. H. Williamson, T. L. Theis, and S. E. Powers. 2003. This study presents results of a life cycle inventory (LCI) of toner used in the xerographic process. Results were intended to be used as a baseline for comparison of future alternatives, but could also be used as a data source for more comprehensive studies of the entire print system.

[9] Mayers, C. K., C. M. France, and S. J. Cowell. 2005. A case study of HP printer recycling in the United Kingdom. LCA 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 Waste Electrical and Electronic Equipment Directive (WEEE 2003).

[10] Stobbe, L. 2007. The EuP Preparatory Study is the result of extensive research conducted by the Institut fur Zuverlassigkeit und Mikointegration (IZM) consortium with the collaboration of industry and stakeholders. Six product case LCAs are performed, including electrophotographic multifunctional copiers (monochrome and color), laser printers (monochrome and color), and inkjet multifunctional printers (personal and workgroup).

Customer Carbon Calculators

[11] Xerox. 2008. 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.

[12] Hewlett-Packard 2009. The HP Carbon Footprint Calculator for printing gives users a use-phase estimate of the electricity cost and corresponding carbon dioxide (CO_2) emissions that result from the production of that electricity. The cost and carbon footprint of the paper used are also estimated.

Table 1 Summary of studies included in the analysis

[Study] Author(1)	*Practitioner*(2)	*Data source*(3)	*Data class*(4)	*Product*(5)	*Purpose*(6)	*LCA Type/Goal*(7)
External marketing						
[1] Koehler 2010	Device manufacturer	Xerox	Specific imaging equipment	Solid ink and laser MFDs	Marketing	Comparative LCA: Technologies
[2] Berglind 2002	Academia: University of Kalmar	Tepro	Cartridges and toner	HP cartridge C4127X	Marketing	Comparative LCA: Remanufacture
[3] Four Elements 2008	Consultant	HP, FEC	Cartridges and toner	HP LJ 10A and remanufactured cartridges	Marketing	Comparative LCA: Remanufacture
Design and decision tool development						
[4] Ord 2009	Device manufacturer	HP	General imaging equipment	Inkjet printer	Design	Internal design tool
[5] Ebner 2009	Device manufacturer	Xerox	General imaging equipment	Printers	Design	Design directional indicator
[6] Silva 2006	Device manufacturer, Academia: University of Kentucky	Lexmark	General imaging equipment	Not applicable	Design	Design stage sustainability scoring
[7] Kerr 2001	Academia: Lund University, Royal Melbourne IT	Fuji-Xerox	Specific imaging equipment	Photocopier remanufacture	Design	Comparative LCI: Remanufacture
Policy						
[8] Ahmadi 2003	Academia: Clarkson University	Xerox	Cartridges and toner	Toner	Policy	LCI: toner
[9] Mayers 2005	Academia: University of Surrey	HP	General imaging equipment	HP printer waste	Policy	Comparative LCA: End of life
[10] Stobbe 2007	Consultant/ Academia	Fraunhofer IZM, Energy Star Database	General imaging equipment	EP & IJ printers, copiers and MFDs	Policy	Industry baseline LCA
Customer calculators						
[11] HP 2009	Device manufacturer	HP	Customer calculator	Personal and office printers	Customer calculator	Cost and carbon calculator
[12] Xerox 2008	Device manufacturer	Xerox	Customer calculator	Personal and office printers	Customer calculator	Compare baseline and optimized print scenarios

Note: LCA = life cycle assessment; LCI = life cycle inventory; HP = Hewlett-Packard; IJ = ink jet; EP = electrophotographic; MFDs = multifunctional devices. (1) Each study is designated by the first author and year of publication. (2) Practitioner describes the affiliations held by the primary author at the time of the study. (3) Data source describes the organizations that worked with the primary author to supply product-related data. (4) Data class generally describes the products examined. (5) Product specifically describes the product, component, or technology examined. (6) Purpose is divided into one of four intended audiences. (7) LCA type/goal is a high-level abbreviated summary of the purpose of the study from the perspective of the original authors.

Study Comparison

Goal and Scope Definition

The definition of goal and scope is essential to identify the impact areas that LCA focuses on, including the necessary assumptions and omissions of the assessment. The goal and scope definition incorporates three areas: the context of the study, the functional unit chosen as the basis of the assessment, and the system boundaries of the assessment. In the following sections we will examine the selected LCA studies on the basis of this framework.

Context

The context within which a study is conducted plays an important role in the decision-making process for assumptions and omissions made in the analysis (Wenzel 1998). Organization affiliations and the intended purpose of the studies are two important aspects of context. Organizational affiliation is represented by the practitioner type (discussed above) and the data sources, which refers to the organizations that supplied the primary author with the product-related data. In many cases this source was the manufacturer of the product analyzed in the study. If a class of products was identified, then alternative sources of data are identified instead (e.g., Stobbe 2007). The intended purpose categories, defined above, are repeated here: External Marketing, Design, Policy, and Calculators. The LCA type/goal is a high-level summary of the purpose of the study from the perspective of the original authors. These aspects of context are summarized for each study in table 1.

Functional Unit and Assumptions

The functional unit defines the output by which products will be compared, and to which all of the analysis parameters are therefore normalized (Reap et al. 2008a). ISO defines the functional unit as the "quantified performance of a product system for use as a reference unit" (ISO 2006b, 4), and as "necessary to ensure comparability of LCA results" (ISO 2006a, 12). Defining a functional unit for imaging equipment is complex due to the multitude of functions that a particular product can perform for a consumer. For example, multifunctional devices (MFDs) combine scanning, faxing, copying, and printing into one machine. Even in the case of a single-function device (printing), the range of uses for the device can vary widely based on the purpose of the printed output and the postprinting operations required; this variation will have an impact on the definition of the functional unit. In addition, 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 is presented in table 2. In the studies reviewed, the functional units took the following forms: pages printed in a fixed time period, a specified print job, a volume of material, and a unit of information. This last unit enables comparison with communication media other than print.

In addition to considering the functional unit, it is also important to understand the useful life of the imaging device in order to allocate reference flows on the basis of the functional unit. However, there can be variability in what is assumed to be the useful life of a device. It depends not only on when the

Table 2 Functional unit and print characteristic assumptions

		Print characteristics assumptions				
Study	*Functional unit*	*Print speed (ppm)*$^{(1)}$	*Total print volume (pages)*$^{(2)}$	*Monthly print volume (pages/month)*	*Average page coverage*$^{(3)}$	*Time period*$^{(4)}$
[1]	Pages/month over useful period	50	1,200,000	25,000	5%–6%	4 years
[2]	Pages by coverage for time period	17	30,000	2,500	5%	1 year
[3]	100 one-sided pages$^{(5)}$	25	100	N/A	N/A	N/A
[4]	One image printed	UI	UI	N/A	N/A	UI
[5]	Unit of information$^{(6)}$	UI	10,000,000	N/A	5%–6%	UI
[6]	5 functional years	N/A	N/A	N/A	N/A	N/A
[7]	Four photocopier life cycles$^{(7)}$	100$^{(8)}$, 65$^{(9)}$	12,000,000	100,000	N/A	10-year maximum
[8]	1 metric ton of toner	135	22,000,000	611,111	6%	3+ years
[9]	21.6 tons of printer waste$^{(10)}$	N/A	N/A	N/A	N/A	N/A
[10]	Average daily use pattern (pages/job)$^{(11)}$	N/A	N/A	N/A	N/A	N/A
[11]	Variable; pages/year and printer life$^{(11)}$	UI	UI [10,000]$^{(12)}$	UI [833]$^{(12)}$	N/A	UI [5 years]$^{(12)}$
[12]	Images/month; annualized	UI	UI	N/A	N/A	Annualized

Notes: N/A = not available or not provided; UI = user input variable data. (1) Prints per minute. (2) Total print volume is defined by the number of pages printed over the study time period. (3) Area of paper that is covered by ink for a text document. (4) Time periods are either time limitations on the study or the expected useful life of the device. (5) Each cartridge is estimated to last through 6,000 one-sided pages according to the ISO/IEC 19752 standard (ISO/IEC 2004). (6) A4 impression with average coverage. (7) Study compared life cycles of manufactured versus remanufactured devices, but these were the use phase assumptions that would have been used based on product specifications. (8) Xerox 5100 copier specifications. (9) Xerox document center 265 DC specifications. (10) This study did not evaluate product use phase, and therefore print characteristic assumptions could not be characterized. (11) For studies where a large number of products can be assessed using a database of assumed printer speeds and monthly print volumes, specific volume assumptions are not listed here because of the large number of data points. (12) Bracketed values are default settings used when user inputs are not available. The numbers in square brackets refer to the studies listed in Table 1.

machine is expected to go into disrepair, but also when a machine is expected to be replaced due to advances in technology (instead of loss of functionality). Factors such as changes in the market expectations for the products, modularity, and serviceability all further complicate estimation of the product's useful life. Within the surveyed literature, the projected useful life of imaging equipment ranged from two to eight years. This range is somewhat consistent with Silva and colleagues, who state that "it is generally known that the maximum number of functional years for a printer is set at 5 years" (2006, 4). An alternative to defining the life expectancy in useful years is to define it in terms of the number of pages or images[1] printed during the life of the device.

Table 2 also provides key printer and usage characteristics used in the studies, where available. Printer speed and the time period (a measure of life expectancy) are characteristics related to the imaging device. The monthly print volume (measured in pages) and average page coverage (a measure of the fraction of the page that is covered with marking materials) are characteristics determined by user. For the cases where usage assumptions are documented, it is clear that standard industry averages were used. The use of 5% to 6% average coverage is consistent with the standard assumption that is used to determine cartridge yield (ASTM 2011). Figure 1 shows the relationship between printer speed and the monthly print volume. When compared to the Energy Star Qualified Imaging Equipment Typical Electricity Consumption (TEC) test procedure (U.S. EPA 2007), it is evident that a standardized approach is being used across the studies to derive the monthly print volume usage assumptions. This standardized approach, however, does not capture the wide variation that occurs in actual use. In the case of print, where the impacts are dominated by paper and consumable use (Ebner et al. 2009), this variability will have a significant effect on the impact calculations (figure 1).

Life Cycle Inventory

Most of the studies examined, including the design decision tools, 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 also varies. In general, two sources of preventable data quality issues typically occur: those due to data gaps and those due to the use of proxy or generic data (Reap et al. 2008b). When an LCA is performed, practitioners often note difficulty in obtaining accurate data. In fact, five studies specifically note that this difficulty impacted their use of LCAs (Berglind and Eriksson 2002; Ebner et al. 2009; Ord et al. 2009; Silva et al. 2006; Stobbe 2007). Many of the studies included sensitivity analyses that used different assumptions for uncertain parameters, such as recycling rates. Unless specifically stated, it is hard to discern why certain data have been omitted.

To get a better idea of data inclusiveness and data quality, we used a grading system of A to E, similar to that used in Boguski (2010), to evaluate the level of detail at which each life cycle stage was explored. An "A" meant that the primary

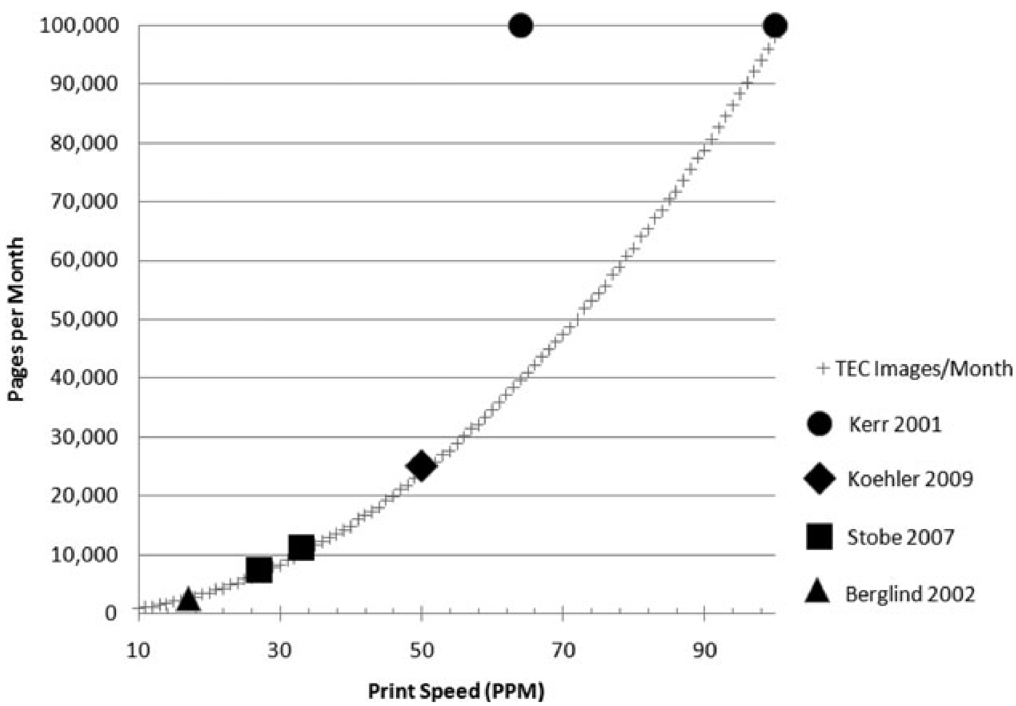

Figure 1 Required paper volumes of Energy Star Imaging Equipment Typical Electricity Consumption (TEC) procedure compared with study assumptions (12 to 100 pages per minute). TEC images/month has been calculated using the TEC procedure to determine the assumed pages per month for printers with a speed of 12 to 100 pages per minute.

Table 3 Ratings of data quality

	Marketing[1]			*Design Tools*[2]				*Policy*[3]			*Calculators*[4]	
Study	*[1]*	*[2]*	*[3]*	*[4]*	*[5]*	*[6]*	*[7]*	*[8]*	*[9]*	*[10]*	*[11]*	*[12]*
Stage												
Raw materials	B	B	B	B	C	B	C	B	C	C	D	C
Production	B	B	C	B	C	E	C	A	E	C	C	C
Transportation[5]	B	B	B	C	B	E	C	B	E	B	D	D
Use	B	B	B	C	B	B	E	B	E	B	B	C
End of life	B	B	B	C	B	B	B	B	B	B	D	C
Packaging[5]	B	B	B	E	C	B	D	C	B	C	D	B

Notes: 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: Excluded due to lack of applicability to study goals. (1) LCAs supporting an external marketing message. (2) LCAs supporting design and business decisions. (3) LCAs informing policy. (4) Calculators to inform customers. (5) These parts of the life cycle are typically included in the production phase. The numbers in square brackets refer to the studies listed in Table 1.

data were measured on site during the phase in question and all relevant aspects seem to have been accounted for. A "B" was given when the data were taken from a database or referenced literature. A "B" may also be missing part of a process. "C" indicates incomplete data or estimates, but the data are still representative of some impacts in this stage. "D" indicates that the data were not included in study scope, and "E" means that the stage was excluded due to a lack of applicability to study goals. The results of this grading effort are shown in table 3.

Transportation and packaging were lacking high-quality data across the studies evaluated here and are ignored in many of them. Raw materials acquisition is 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 is to retrieve database impact attributes based on masses from a bill of materials obtained by disassembling the product. These product component masses are not preferable, especially for electronics with semiconductors, as input materials can have a mass that is much greater than that of the final product (Williams et al. 2002). It is also 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 its accurate estimation, 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 examined studies could be scored an "A."

The raw materials acquisition and manufacturing are two life cycle stages that have relatively high impacts in atmospheric and waterborne emissions (U.S. EPA 1993). However, in the studies reviewed here, these two stages are sparsely populated. Many LCAs are criticized for uncertainties or inaccuracies surrounding impacts from component manufacture processes, as often the materials used can be identified but the exact processes used cannot. 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" (Berglind and Eriksson 2002, 2). Again, this supports a need for greater dissemination of upstream data in the supply chain. The two studies that were missing this stage were either focused on end of life (Mayers et al. 2005) or simply omitted it because other aspects were thought to have greater impact (Silva et al. 2006).

In nearly all of the studies examined, the electricity and paper used during the use stage were said to have had the most significant impacts for the imaging device. Both of the impacts are greatly influenced by the actual behavior of the user. For example, the extent to which power-saving settings on imaging devices are used will affect energy consumption. Similarly, the use of double-sided printing and print preview functions will impact actual paper consumption rates. This highlights the importance of the use stage, and the need for accurate and representative user characteristics with respect to device settings and habits in order to properly assess the environmental impacts.

End of life is another stage of the life cycle where large discrepancies exist in LCA practices, and the print industry is no exception. A major contributor is that waste management differs by locality, and not all options can be taken into account, therefore the use of different assumptions of waste management types for a given product can lead to different assessment results (Shen and Patel 2008). Remanufacturing, recycling, and reuse of equipment and consumables are other areas of debate for the printing industry because the benefits of these practices can be greatly influenced by the underlying assumptions of the analyses. All of the design tools examined in this work have included remanufacturing in some form in their analyses.

There were some sources of data that were used across several studies. The Energy Star standard (U.S. EPA 2007) and database are used frequently in these studies for several reasons. Having a set procedure (e.g., TEC) is useful for a program like Energy Star to standardize usage assumptions for classes of products. Likewise, such a standard procedure is useful when measuring energy use for LCAs. This standard procedure is also appealing because it is specific to imaging equipment. Many products also seek certification, so products being studied by an LCA may have already had TEC measured, making it an efficient choice for manufacturers. If a study is conducting policy analysis, the Energy Star database is attractive because it contains data for a large group of manufacturers, and all had to follow the standardized TEC procedure. The Intergovernmental Panel on Climate Change (IPCC 2006) is also cited frequently for the standard treatment of 100-year global warming potential (GWP). All but two of the studies determined impacts for GWP, and this is one of the few impact categories with a clear set of guidelines.

Life Cycle Impact Assessment

Life cycle assessment publications that intended to differentiate products based on their environmental impacts generally focused 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 marketing reviewed in this work. Practitioners selectively limit the number of impact categories so as not to overwhelm the reader with information that is, relatively, less important. Even though Koehler and colleagues (2010) were using a SimaPro software tool (PRé Consultants 2006) that includes multiple impact categories within multiple impact methodologies, the researchers decided to limit the results to greenhouse gases (GHGs), energy use, and solid waste. The danger in limiting impact categories to a handful is that their impacts have to be normalized to determine significance relative to one another. For example, the impact on human toxicity may be small in comparison to GHG emissions, but the visibility of this impact may be such that its weight is greater to the communities affected by it. Studies performed in academia are more likely to include all impact category results, even if they are very small or not relevant. Figure 2 shows impact categories by study audience. Note that what is shown in figure 2 is the relative frequency of each category within a context group. This relative frequency is scaled to four to match the scale that is used later in this review to assess the degree of inclusiveness.

Excluding energy use, global warming was the leading impact category of the studies. This is likely due to the importance placed on GHG emissions in recent years. There is also a universally accepted standard unit of measurement (IPCC 100-year GWPs). Impacts of ecological toxicity and human health typically get less attention, even though this would seem to be a priority impact (Reap et al. 2008b). Resource depletion also 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.

Life Cycle Stage and Impact Category Coverage

We also explored the relationship between study context (i.e., Policy, Marketing, Design, and Calculator), the inclusiveness of impact categories, and the degree to which the life cycle stages were addressed in the studies. To assess the inclusiveness of impact categories, the number of studies within each context group that had included the impact category were taken from figure 2 and averaged across all impact categories for each context group. Results are shown in figure 3. Similarly, to assess the degree to which the life cycle stages were addressed, the grades from table 3 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. With a four-point rating system, these grades were simply averaged by study and then by context group for inclusion in figure 3.

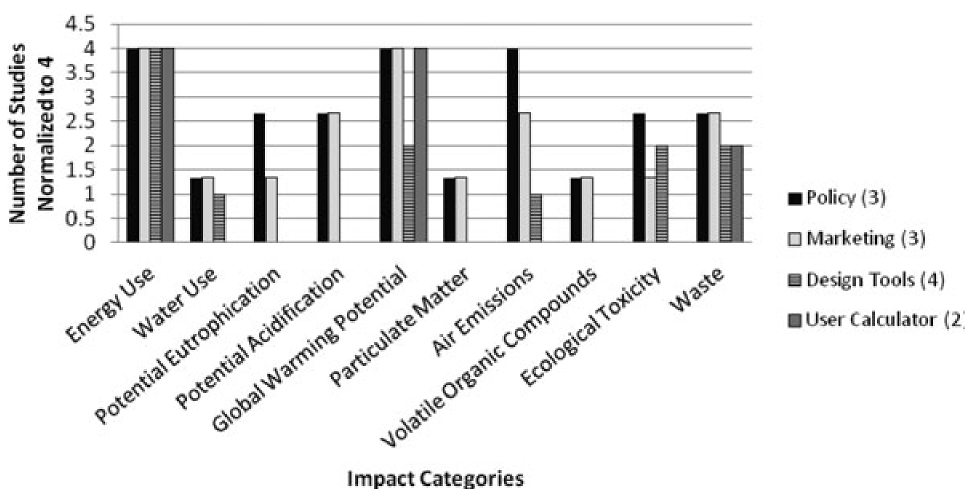

Figure 2 Impacts included based on the primary intended audience of the studies. The number of studies targeted to each audience group is indicated in parentheses.

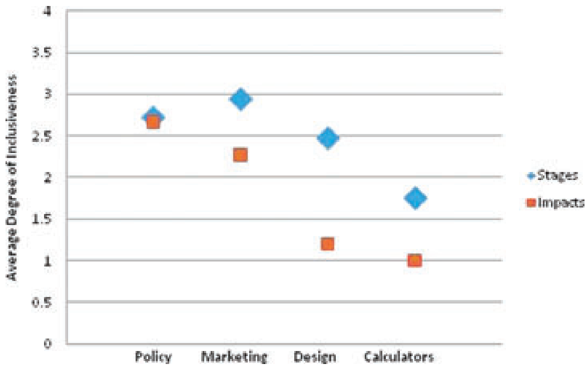

Figure 3 Degree of inclusiveness of impacts and stages for each primary intended audience.

As seen in figure 2, policy was the most inclusive of the 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 highest coverage of the life cycle stages, but the policy studies had a similar result. It was interesting that studies for external marketing were more inclusive for both impacts and stages than those for internal design. This suggests that either the impact and stage inclusiveness requirements for informing design decisions may not be the same as those needed for communicating with external stakeholders, or that these tools have a harder time getting the information they need to fulfill their purpose. Not surprising is that the impacts typically included for external marketing—carbon emissions and waste—are also typically included in customer calculators.

Discussions and Conclusions

This article reviewed 12 LCA studies directly related to the environmental impacts of imaging equipment for consumer markets. This review applied the ISO 14040 framework as a way to systematically compare the studies and look for similarities and differences. The key elements that were examined in this comparison were the context of the studies, the resulting functional units, the system boundaries, and the associated life cycle stages and impacts that were included. This examination was followed by an analysis that aggregated these observations into an assessment of the breadth of the studies by intended purpose (which is related to the context of the study). This was measured by averaging the data quality assessments over all life cycle stages. The analysis also examined the depth of these studies as a function of intended purposes by performing a weight averaging of the number of studies that referenced a particular impact category. The remainder of this section will discuss the significance of these results, draw key conclusions, and discuss future opportunities.

Key Findings

Defining the functional unit for imaging devices is complicated by the multiple functions that can be performed by the device and the variety of outputs that can be produced by the same device. We discovered variety not only in the functional units defined, but also in the forms of these functional units. Given the role that the functional unit definitions will play in the consistency across different assessment efforts of printing systems as well as the challenges outlined above, this represents an opportunity that is ripe for further research, particularly dealing with the multifunctional aspects of products.

This is further complicated by the fact that functions fulfilled by the printed output are being challenged by other forms of information communications technologies, such as email or other electronic files. The importance of this trend is that it creates a need for functional units that allow for comparison between these two forms of communication. By employing approaches such as those that use a functional unit based on a "unit of information," these types of comparisons will be enabled, allowing studies like those described here to remain relevant when compared to new forms of media (Hischier and Reichart 2003).

Another key observation relates to the characteristics of the users' behaviors. In printing particularly, the use patterns of the device will have a major influence on the LCA result because paper use is one of the dominant contributors to life cycle impacts (Ebner et al. 2010). In our review we discovered that when it comes to use patterns, the norm is to use industry averages. This was evident in the monthly usage profiles and the print content coverage assumptions that were made in the various studies. While use of these standardized approaches and numbers is understandable, a better job needs to be done integrating more realistic use profiles into the LCAs. It is interesting to note that the TEC background information states "it is important to emphasize what the TEC test procedure is not intended to do. It is not intended to provide a best estimate of average consumption of a product in actual use" (U.S. EPA 2005, 9).

It was found that most studies did consider all life cycle stages to some degree. The stages that were covered least included raw materials acquisition, manufacturing, transportation, and packaging. The two major contributing factors to the lack of coverage of these stages are difficulty collecting data from the supply chain and the large fraction of total impacts contributed by paper.

Study Limitations

One of the limitations of this study is that it was based on published documentation, which is limited in the level of detail that is provided on the models and data used in the LCA study. One factor that contributes to this limitation is that the primary goal of many of the reports we reviewed was to inform consumers and potential customers, therefore those reports were simplified so as not to overwhelm readers with details. Even for those studies more academic in nature, authors simply cannot put all the data into a single paper. While some limited efforts were made to contact study authors in industry, this met with limited success for a variety of reasons. A dominant reason was that much of these data are considered sensitive by the industry, and the incentive to share detailed information is low. As a result of this limitation, the review of the depth of the data used in studies in the boundaries section may have missed the real depth of the studies assessed. In future work, one way to address this problem would be to conduct interviews with study authors.

The studies reviewed also exhibited a regional bias. The majority of the industry papers reviewed were from companies headquartered in the United States. Efforts were made to avoid this bias with studies from Australia and Europe.

Opportunities

The objective of this review was to better understand how potential inconsistencies in environmental impact assessment were being realized. This was accomplished by comparing life cycle stages and impact categories examined by each study. With the data that were publicly available, we observed that studies focused on policy issues and external marketing more thoroughly examined the life cycle stages and included the greatest number of impact categories. In contrast, those studies focused on tool development (design and calculators) were less thorough and covered fewer impact categories. This represents a research opportunity to develop streamlined and higher quality environmental impact assessment methods to support decision-making processes.

Our own interaction with the industry revealed a widespread interest in developing some level of standardization in print-related LCAs. Consumers of LCAs are interested in increased comparability, while practitioners are interested in streamlining the LCA process with standard and industry-specific data sets, assumptions, and processes. Standardization of the functional unit and the assumptions that are interwoven within it have a high potential to increase quantitative comparability across studies. Assumptions that are not standardized lead to difficulties in comparisons between studies. At the same time, caution to not define imaging device functions by paper usage allows for comparison to alternative media. Some of the most significant assumptions are those on use behaviors. Consumer behavior has the potential to be the greatest environmental impact reducer, namely by reducing misprints or the necessity of printing altogether. The only way to quantify these differences is to gather extensive use data. A sensitivity analysis should also be included with these behavior data, as they are highly variable.

End-of-life impacts may be another area where standardization can help. There was little agreement between studies on how materials would be disposed of. Assumptions surrounding portions that are reused, remanufactured, recycled, burned for energy, archived, or landfilled are all variable. These differences can lead to very different results (Shen and Patel 2008), mainly due to the impact of paper (Counsell and Allwood 2007). There have been several attempts to determine from where such disagreement stems (Finnveden and Ekvall 1998; Villanueva and Wenzel 2007). While some of the differences may reflect actual differences in disposal, some suggest that much of the difficulty in accounting for the variability in disposal assumptions is due to the disposal's distance from the practitioner, with the user deciding how to dispose of the product and consumables at an unknown time and place (Ebner et al. 2009). One option for standardization of this part of the LCA may be to take an approach similar to that already used for energy production, where regionally specific databases set the standard for assumptions regarding where products are disposed at end of life. This is something that would benefit both LCA users and practitioners.

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Note

1. Images are a useful measure because there often are images on both sides of the page.

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