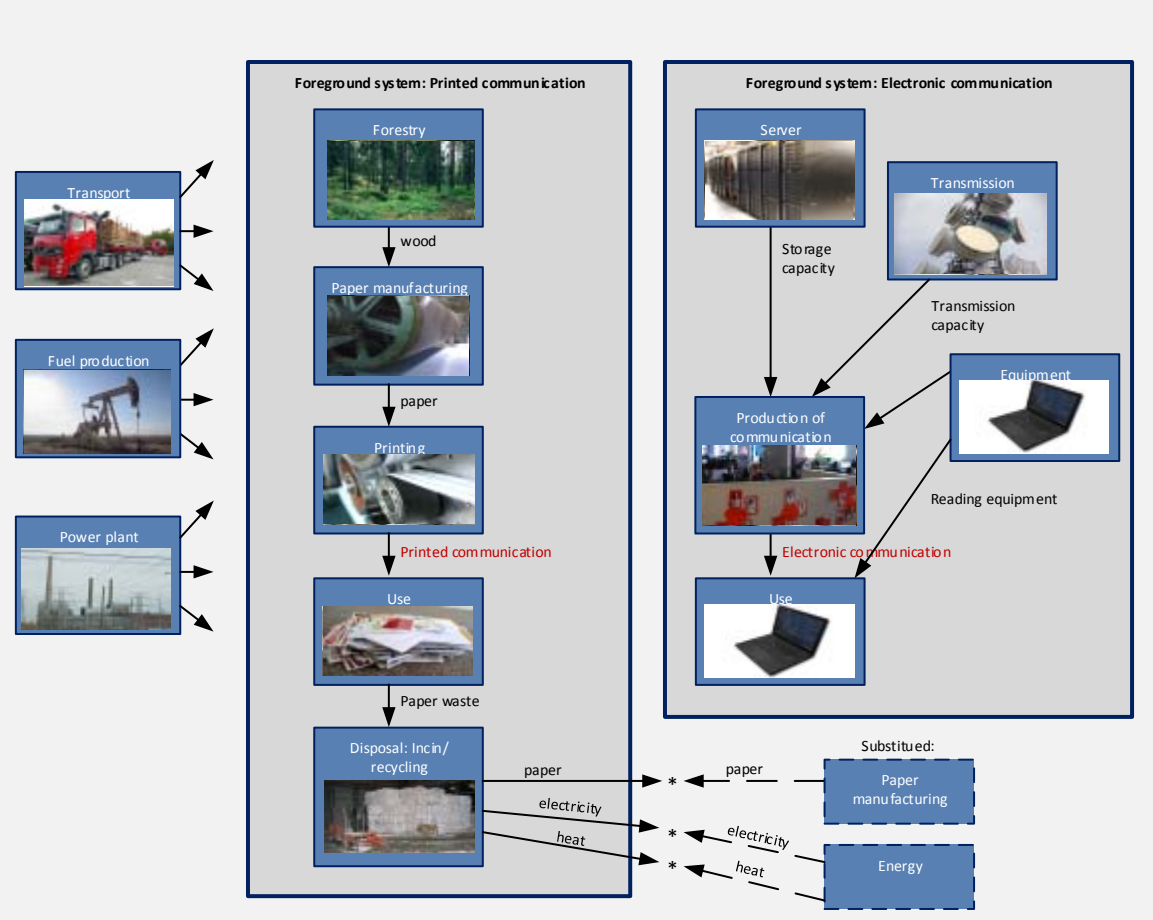
Critical review of four comparative life cycle assessments of printed and electronic communication



GRAFISK ARBEJDSGIVERFORENING

Preface

This report is carried out by Jannick H Schmidt (2.-0 LCA consultants, Denmark) and Massimo Pizzol (Aalborg University, the Danish Centre for Environmental Assessment) for the Graphic Association of Denmark. The study was undertaken during October and November 2014.

Jannick H Schmidt and Massimo Pizzol, Aalborg, Denmark, 4th December 2014

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1 Introduction and background

In society as well as in the graphic industry there is an ongoing debate about the environmental impact of printed communication compared to electronic communication. The four selected LCA studies in this critical review all aims at comparing the overall environmental impact of different types of printed communication with an alternative electronic communication. The conclusions of the studies are not consistent in favour of one specific communication method. Since all the reviewed four studies are frequently cited in the debate it is essential to uncover whether the four studies have a quality and scope that make them suitable to conclude that one communication method is better than the other. Besides reviewing the studies' suitability for comparing communication methods, the critical review also focus on pointing out which issues that need to be covered in order to perform a suitable comparable study of the two communication methods.

The reviewed studies were selected by the Graphic Association of Denmark (GA). The reviewed studies are:

- **Sanchez V M and Møller J (2011)**, LCA on the prevention of unsolicited mail in the Vestforbrænding municipalities. DTU Environment. Kgs. Lyngby.
- **Schmidt A and Kløverpris N H (2009)**, Environmental impacts from digital solutions as an alternative to conventional paper-based solutions. e-Boks.
- **Moberg Å, Johansson M, Finnveden G, Jonsson A (2009)**, Screening environmental life cycle assessment of printed, web based and tablet e-paper newspaper, Second edition. Reports from the KTH Centre for Sustainable Communications. Stockholm.
- **Enroth M (2009)**, Environmental impact of printed and electronic teaching aids, a screening study focussing on fossil carbon dioxide emissions. Advances in Printing and Media Technology, Vol. 36, 2009.

2 About life cycle assessment

Life cycle assessment (LCA) is a technique to assess environmental impacts generated by a product or service from 'cradle to grave', that is, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. The general procedures, requirements and terminology of LCA are defined in the international standards on LCA ISO 14040 and 14044.

2.1 An LCA has four phases

The phases of an LCA characterise individual (iterative) phases of the process of conducting an LCA study and most often LCA studies are also documented following these four phases. The phases are:

1. Goal and scope definition.
2. Life cycle inventory (LCI).
3. Life cycle impact assessment (LCIA).
4. Life cycle interpretation.

2.2 Functional unit

The functional unit is central for an LCA. The functional unit is a quantified performance of a product system (see **Figure 1**) for use as a reference unit, i.e. it is what all the results relate to. For comparative LCAs, it is crucial that the compared systems deliver the same functional unit, i.e. that they are comparable on the same basis.

2.3 Product stages and foreground/background systems

An example of how the main stages of the life cycles of printed and electronic communication can be defined are illustrated in **Figure 1**. The boxes in the figure are called activities, and the arrows represent flows. Often the activities in a life cycle system are grouped in a foreground system and a background system. The foreground system includes the LCA activities for which data are collected and modelled in the study while the background system include the activities for which generic and existing data are used, i.e. often from LCA databases.

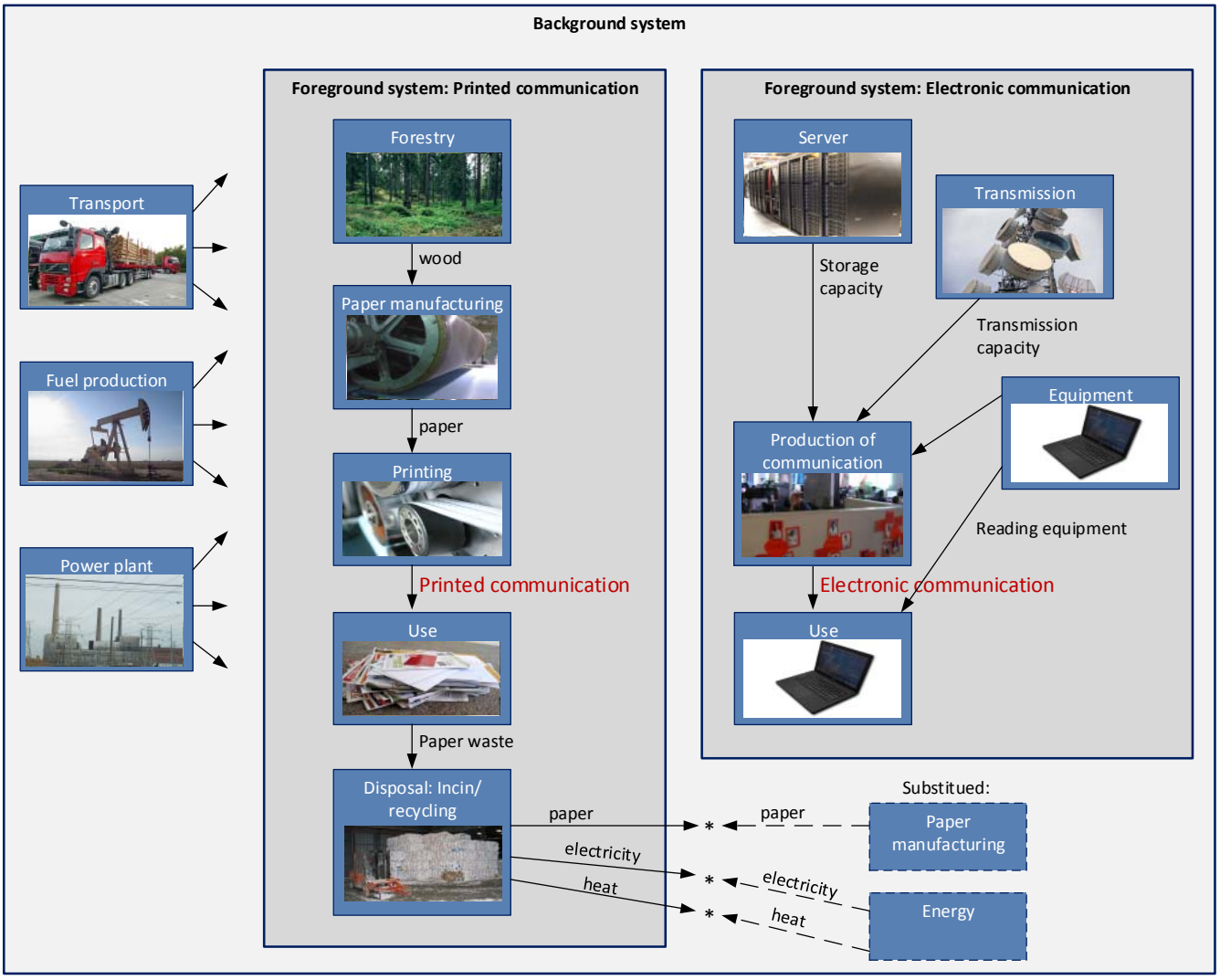

Figure 1: Example of how the main stages of the product systems for printed and electronic communication can be defined. Dotted lines and boxes represent negative flows and substituted activities respectively. Pictures: Wikimedia.

2.4 System boundary and life cycle emissions

The outer boundary of **Figure 1** represents the system boundary, which is the boundary between the technosphere (alternatively identified as the economy, i.e. where the human activities are) and the environment. Each activity in the system may generate emissions and have inputs of resources. These are defined as environmental exchanges from/to the technosphere to/from the environment, i.e. substance flows (or other such as noise, radiation, land use) that cross the system boundary. The sum of all environmental exchanges that cross the system boundary is the life cycle inventory analysis result (LCI result) related to the product under study. The LCI result is often referred to as life cycle emissions.

2.5 By-products

Some of the activities in **Figure 1** supplies by-products, e.g. the disposal stage of the printed communication includes paper recycling which supplies the by-product: 'paper', and waste incineration which supplies the by-products 'electricity' and heat'. The way to model by-products in LCA is to include the induced substitutions. These substitutions are indicated by dotted lines in **Figure 1**.

2.6 Life cycle impact assessment (LCIA)

Most often an LCA software is used for calculating the life cycle inventory. The number of calculated different environmental exchanges is often very high – especially when collecting detailed data and when linking to large databases for the background system. It is not unusually that 500-1000 different emissions are included in the life cycle inventory analysis result. Presenting and interpreting so many emissions individually is not meaningful. Therefore, a so-called life cycle impact assessment (LCIA) is carried out. This implies that the environmental exchanges are 'characterised', which means that e.g. each of the different emissions is multiplied by a 'characterisation factor' that represents the emissions' relative contribution to a certain impact category. For each impact category included, an aggregated result is produced, in a given unit of measure. For example, Global Warming Potential is calculated in kg CO_2-eq. from the contribution of CO_2, CH_4, and N_2O emissions, among others. The principle of characterisation is illustrated in **Figure 2**.

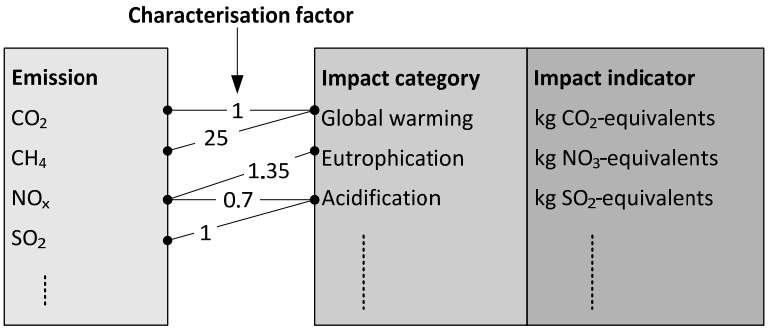

Figure 2: The principle of characterisation.

2.7 Uses of LCA

LCA can be used by decision makers to fulfill several objectives:

- To provide a picture as complete as possible of the interactions of an activity with the environment.
- To identify major environmental impacts and the life-cycle stages or "hot-spots" contributing to these impacts.
- To compare environmental impacts of alternative ways to produce the same product.
- To identify improvement options.

Further, LCA has many application areas, such as (ISO 14040):

- Environmental performance evaluations
- Environmental labels and declarations
- Environmental communication
- Quantification, monitoring and reporting of entity and project emissions and removals and validation, verification and certification of greenhouse gas emissions

3 Review methodology

The method applied in the analysis can be defined as a combination of systematic review and expert assessment.

The scope of the analysis is limited to the four studies mentioned in the introduction. These are four LCA studies that address the issue of what is the environmental impact of printed and electronic media.

When referring to printed and electronic (web based) communication throughout the review these alternatives will be named ”Printed” and ”Electronic”. For the Moberg et al (2009) study, the third alternative (e-paper) will be named “Tablet”.

The starting point of the review is a systematic review which is performed to obtain a synthetic overview of each study and facilitating the comparison by identifying common elements and distinguishing aspects. The systematic review compares the four studies on a fixed set of attributes and a “review matrix” is established. This consists essentially in a table where the study names represent column headings and each attribute represents a different row heading. The attributes were selected inspired by similar peer-reviewed studies, in particular the systematic reviews performed by Corominas et al. (2013) and Pizzol et al. (2014). Different attributes were identified for each of the four phases of LCA: 1) goal & scope, 2) inventory, 3) impact assessment and 4) interpretation. Examples of attributes that have been systematically reviewed: (what is the) scope of the study; (what is the) functional unit of the study; (what are the) life cycle stages included in the study; etc. The full review matrix is provided as supplementary material (Appendix A). The results section focuses on the comparison and commenting of specific attributes deemed as the most important and relevant for benchmarking the four studies.

The expert assessment is the authors’ critical reflection on selected critical issues. The authors have analysed how the four studies have dealt with general LCA challenges as well as challenges specific to the case of printed versus electronic media. This part of the analysis is meant to answer questions such as: How was this critical issue addressed in the four LCA studies? Are the solutions appropriate according to current scientific standards and knowledge available? Could this have been done otherwise? Etc. The selection of these issues is based on the “hot spots” identified by the four LCA studies as well as the reviewers general knowledge on and experience of which issues are critical in LCAs applied to different product types. Critical reflections are to the largest extent made based on scientific arguments, i.e. striving for objectivity but obviously maintain a degree of subjectivity. Wherever possible, references and data are provided to support the authors’ claims.

The review is structured following the four phases of an LCA, see **section 2.1**.

4 Review of four comparative LCA studies on printed and electronic communication

4.1 Goal and scope definition

This section presents and compares the overall characteristics, purpose and methods of the four reviewed LCA studies.

Type of study

The key reference for life cycle assessments is the ISO 14040 and 14044 standards. These standards define the LCA terminology and the overall requirements to LCA studies: the process of conducting LCA studies, methods, data, evaluation, documentation etc. Therefore, if a study is ISO 14040/44 compliant, this indicates a certain level of credibility of the studies, though it does not provide a guarantee of being a scientific valid and robust study.

Table 1: ISO 14044.

Does the study claim to be ISO 14044 compliant?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
No.	No.	Defined "as close as possible to the requirements published in the ISO 14044 standard, but it does not follow it strictly."	No.

It appears that no of the compared studies are claimed to be ISO 14040/44 compliant.

Table 2: Study type and peer-review.

What kind of study is it and did it receive a critical review?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Journal Article (conference proceeding), publicly available 9 pages Probably peer-reviewed (by conference committee)	Report, publicly available 106 pages Not specified if peer reviewed or not	Report, publicly available 120 pages One Danish External reviewer (COWI)	Report, publicly available 57 pages Workshop with external experts to discuss initial idea. Same experts commented on draft report. Not clear if revisions were mandatory and feedback was sent to reviewers (as in peer-review process)

The study of Enroth is the most synthetic, whereas the others are large reports. The review process is thoroughly documented only in Sanchez and Møller (2011), which includes comments and answers in the report. In general the review process of the four studies can be considered weak compared to the ISO standard's requirements, i.e. that comparative assertions to be disclosed to the public shall undertake a critical panel review by at least three reviewers.

Problem formulation, objective and purpose

Table 3: Problem formulation.

What is the study's problem formulation, hypothesis, or rationale?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Teaching aids have a longer lifetime compared to other media (newspapers, mail) and can be used by many users, so the printed ones may have a lower environmental impact than the electronic ones.	Using tablet e-paper rather than printed newspaper avoids paper use and physical distribution of the printed paper. The e-paper device has lower energy use during downloading and reading as compared to using a computer for reading newspapers on the web. Thus, tablet e-paper should have lower impact than printed and web based newspapers.	Avoiding unsolicited mail arriving to Danish households with the "Commercials - no thanks" scheme. Prevention of unsolicited mail avoids production and distribution of commercials, but less benefit is obtained from paper recycling (less virgin paper to substitute) and from incineration (less energy is recovered from burning the waste).	The digital solution reduces the need for paper and fuel for transportation, but using e-mail uses IT equipment and electricity ("hidden" impact)

Except from Enroth (2009), the studies have similar points of departure: the hypothesis is that the use of electronic media should theoretically lead to savings of resources compared to the use of printed media.

Table 4: Objective of the study.

What is the stated objective of the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Performing a screening LCA comparing electronic versus printed teaching aids.	(i) Describe and compare the potential environmental impacts of three product systems; printed newspaper, web based newspaper and tablet e-paper newspaper (via a screening LCA) (ii) Identify hot spots (most impacting activities) in the life cycle of the three products (iii) Identify data gaps and areas where information is lacking.	(i) Environmental assessment of the scheme "commercials - no thanks" (ii) Support the campaign of Vestforbrænding to encourage citizens to join this scheme (iii) prevent unsolicited and unaddressed advertising in citizens' houses (iv) performing sensitivity analysis to compare the printed commercial with online ones.	(i) Document the environment properties of the e-Boks concept in a life cycle perspective (ii) Compare e-Boks system to ordinary mail distribution system (to boost the competitive advantage of e-boks) (iii) Provide general insights to the public about the digitalization of society.

Except from the Enroth (2009) study, which is a pure research study, the other studies have a similar general objective of decision support for different organizations and for the public. It should be noted that the Sanchez and Møller (2009) study is a study principally addressing waste management although within the study a sort sub-study (that is defined as a sensitivity analysis) is performed comparing printed and web commercials.

Table 5: Goal of the LCA.

What is the stated goal of the LCA?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Comparative LCA of printed versus web-based teaching material.	Compare printed newspaper; web based newspaper and tablet e-paper newspaper.	Describing and quantifying the potential environmental effects obtained when a Danish household (multi family or single family) in one of Vestforbrænding's municipalities joins the scheme "commercials – no thanks".	Quantify the environmental consequences of using e-Boks as an alternative to conventional distribution of documents by ordinary mail.

Three of the four LCA studies compare two different products: a printed media and an electronic media. Again the exception is the Sanchez and Møller (2011) study which compares different scenarios of waste management, although also a comparison of printed and web commercials is proposed within the study.

Function and functional unit

This section described and compares the product under study and the functional unit.

Table 6: Product characteristics.

What exactly is the product under study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Printed teaching material versus web-based electronic teaching material. Teaching aids for students.	Printed newspaper, web based newspaper, and tablet e-paper newspaper. Sundsvalls Tidning (ST), a Swedish newspaper.	Printed commercial newspapers versus online commercials.	E-boks (e-mail) versus paper document for official communications (bank, municipality, etc.).
Printed: textbook of 0.8 kg/book and 5 years lifetime.	**Printed:** Paper version A4 size with 80 g/m2 weight.	**Printed:** unsolicited mail matter is A4 size with paper density of 80 g/m2.	**Printed:** average paper document with weight 13.94 g (1.8 sheets + envelope + glue and toner + acetate window).
Electronic: Use of personal computer for viewing documents is 80 hours.	**Electronic:** newspaper file of 2.5 MB and view is 10 min/day.	**Electronic:** online commercial is intended as 1 minute of online view of a side of A4 of average web size = 320 kB.	**Electronic:** average e-Boks document size at user 38 kB, and two minutes reading time.
	Tablet: 5MB document and 30 min/day of reading.		

The studies compare completely different products. The only thing that these products have in common is that one of the two is printed and the other is electronic (this does not apply to the Sanchez and Møller (2011) study). The products characteristics are specified in good detail, all studies report on the format of the paper used and its weight, and on the size of documents in bytes and the viewing time.

Table 7: Functional Unit.

What is the stated functional unit of the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
"Use of teaching aids for 5 years for 5000 pupils per year (i.e. 25000 pupils years). Each year the pupils use the teaching aid 2 hours per week for 40 weeks. The pupils reside in six different cities in Norway".	"Yearly consumption of newspaper for a unique reader (with 30 min. Reading time)".	"Management of the annual amount of household waste generated by a household in one of Vestforbrænding's municipalities". For the comparison with online commercials, the functional unit is: "same amount of commercials per household is checked out online instead of being received in the mailbox".	"The distribution of 98.5 million documents in 2008 using the e-Boks concept" (= total amount of documents stored in e-Boks in 2008).

The studies adopt completely different functional units. However, all of them identify the performance of a service for a specific amount of time and users based on real-world estimates. Enroth (2009) and Schmidt and Kløverpris (2009) define a functional unit that is in accordance with the goal of the LCA and that provides a good basis for comparison. In Møller and Sanchez (2011) goal of the LCA and functional unit are not consistent. The study wants to evaluate the effects of one household joining a no-commercial scheme, which is a decrease in demand for commercials, whereas the functional unit is defined as the management of waste from a household. Household waste is defined as the "waste generated by a household excluding garden waste, hazardous waste and bulky waste". It is not clear why all other waste fractions beside paper are included, this seems redundant. For the comparison between paper and web based commercials the functional unit is similar to other studies (visualization of document). It is not clear why Moberg et al. (2009) have used a "unique reader" in the study and not the total numbers of readers/users as the other studies have done.

Table 8: Reference flow.

What is the reference flow of the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Printed: 4.0 tons paper.	**Printed:** 58.4 kg paper (730 A4 sheets/unique reader, 80g/sheet).	**Printed:** 55 kg paper commercial.[1]	**Printed:** 1370 tons of paper;
Electronic: 1500 MB.	**Electronic:** 913 MB/unique reader.	**Electronic:** 6875 MB online commercial (320 kB per page and 22000 pages/household/year).	**Electronic:** 3655 GB (38KB/doc and 98.5 million docs).
	Tablet: 61 hours of reading/unique reader.		

The term "reference flow" is not mentioned explicitly by any study, but the necessary information to identify it is reported. There is a difference between functional unit and reference flow because the former answer s to the question "How much function is needed?" and the latter to the question "How much product is needed to perform this function?" The reference flows used in the studies have been back-calculated based on the information available and expressed in the following units to allow for comparison: mass (kg) of paper for the printed media under analysis and bytes (MB) of file size for the electronic media.

[1] The 55 kg waste paper (which is relevant for the comparison printed and electronic), is included in a more comprehensive reference flow of the LCA: treatment of 326 kg of household waste each year (of which 55 kg of unsolicited paper mail).

Table 9: Comparability of printed vs. electronic alternatives within the defined functional unit/reference flow.

Does the functional unit and reference flow provide a real and meaningful basis for the comparison of printed and electronic communication?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
It is assumed that the two compared media for teaching are fully substitutable on a 1:1 ratio of use time. Hence, similar leaning outcomes are assumed per hour of use. Further, it has been assumed that the electronic alternative does not need to be supplemented by any printed information which could be the case.	A reading time for a newsprint at 30 minutes has been assumed. This could be supplemented by empirical data on reading time. Differences in reading time for different media are not considered. Further, the amount of articles read are not considered as being affected by the choice of media.	It has been assumed that households that chose to say 'no thanks to commercials' download and read an equivalent amount of information as the avoided printed commercials. This assumption seem a bit crude.	The comparability of the studied systems is rather well argued. Reading time for electronic communication is based on empirical data. It has been considered that some users print the electronic information.
Difference in costs of the compared media are not considered.	Difference in costs of the compared media are not considered.	Difference in costs of the compared media are not considered.	Difference in costs of the compared media are not considered.

It appears from **Table 9**, that besides the Schmidt and Kløverpris (2009) study, the compared alternatives may not be completely comparable because some aspects are not accounted for. When performing comparative LCA, a key issue is making sure that the two alternatives are compared on the same basis. This implies two conditions: firstly, the two product systems should provide the same functional unit; secondly, all the activities required to provide the functional unit should be included within the system boundaries. In the case of printed versus electronic communication, the substitutability of the two alternatives should be verified. This means answering the questions:

- Do the compared product systems provide the same function? This function could is defined by the purpose of the compared alternatives, e.g. teaching material in Enroth (2009) and commercials in Sanchez and Møller (2011).
- Are all the required activities to provide the functional unit included in all compared systems?

The problems related to comparability in the four reviewed studies are summarised below. These problems include differences in the provided function and the completeness of the included activities.

- Enroth (2009): The learning outcome of the two compared teaching material may be different.
- Moberg et al. (2009): The reading time and satisfactory with the user may be different.
- Sanchez and Møller (2011): The efficiency of the compared advertisement channels may be significantly different. E.g. the printed commercials are delivered right into the target group's physical mailbox, while the electronic commercials are just present somewhere on the internet. It is likely that the efficiency of attracting the target group will be different – the electronic alternative may need to be accompanied by additional activities. These activities, which could include loyalty programs, additional advertising etc., are not considered.
- Schmidt and Kløverpris (2009): The comparability and completeness is supported by empirical data.

Further, none of the studies consider that the compared systems have different costs. A difference in cost will impose an increase/reduction in consumption of other products equivalent to the difference in price. E.g. if the printed media costs 1 DKK per functional unit while the electronic media costs 0.5 DKK per functional unit, the basis for comparison is not real before the change in consumption equivalent to the difference in price is also addressed in the LCA. This can easily be explained by the fact that changing to a cheaper product alternative

will release some money that will be spent on something else. This mechanism is referred to in literature as rebound effect, and the affected type of consumption is referred to as marginal consumption. More information on rebound effects can be found in Thiesen et al. (2008). When including rebound effects, the impact of the cheapest compared alternative will increase. However, it should be noted that it is not common practice that rebound are included in LCA – but this does not make it less relevant.

System boundaries

Table 10: Product's life cycle stages.

What stages of the product's life cycle have been investigated in the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Printed: pulp and paper production, transportation, prepress, printing distribution, use, end of life. Editorial work not included.	**Printed:** paper production, transportation and prepress, editorial work, printing, distribution, reading, end-of-life. Editorial work included.	**Printed:** Collection, recycling, incineration + avoided production of paper.	**Printed:** production of paper and toner, envelope, letters; Printing of document; Distribution; Production of envelope; incineration/recycling of paper; avoided virgin paper and electricity.
Electronic: formatting, internet infrastructure, production, distribution, use and end-of life of computer and electronics.	**Electronic:** content production, production and use of paper (EU), computer and screen production (China); end-of-life (EU). Tablet: content production and use stage (U), tablet production (China), end-of-life (EU).	**Electronic:** energy for computer usage and for downloading and transferring data.	**Electronic:** Production of server, paper, and toner; Distribution, view on pc, and printing of documents; Incineration/recycling of paper; avoided virgin paper and electricity.

All four studies are cradle-to-grave analyses. However, Sanchez and Møller (2011) focus on end-of-life, and then also include avoided upstream effects in the analysis of the electronic communication (avoided production and distribution of printed media).

Table 11: Inclusion of computer and internet infrastructure

Were computer and internet infrastructure included within the system boundaries?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Production, distribution and waste management of personal computers included	Production and waste management of PC and screen ("to some extent") included; Internet infrastructure included in sensitivity analysis (data from USA Input Output database 98)	Production and disposal of equipment (computer) not included	Production of computer not included (assumption that users of e-Boks do not purchase a computer for this specific task alone)

One of the most interesting assumptions in comparing printed and electronic communication is the inclusion of capital goods and in particular of personal computers and internet infrastructure. The studies adopt two lines of thought. One rationale for including these is proposed by Enroth (2009) and Moberg et al. (2009): since a computer has a certain life time and only one task per time can be performed, when viewing electronic communication the computer will not be available for other tasks and part of its lifetime is dedicated to the reading. Therefore, a fraction of the computer will have to be produced in order to perform the function of the system. In an extreme scenario where a computer is only used for reading electronic communication, then the production of the entire computer is necessary to perform the function and should be included within the system boundaries. The rationale for not including these, proposed by Schmidt and Kløverpris (2009) is that

users do not purchase a computer for the specific task or reading electronic communication alone. It is not specified what the rationale for excluding computers is in the study of Sanchez and Møller (2011).

General modelling approach

Generally, there exist two different approaches to modelling in life cycle inventory:

- consequential modelling
- attributional modelling

According to Sonnemann and Vigon (2011, p 132), attributional modelling is defined as: "*System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.*" This often implies that products are modelled as being produced using existing production capacity (current or historical market average), and that multiple-output activities are modelled by applying allocation factors. For waste treatment, e.g. incineration and recycling, there are different approaches.

According to Sonnemann and Vigon (2011, p 133), consequential modelling is defined as: "*System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.*" Hence, in consequential modelling it is generally a change in demand of the product under study that is modelled. A cause-effect relationship between a change in demand and the related changes in supply is intended to be established. This implies that the product is produced by new capacity (if the market trend is increasing). Also it is taken into account that the affected production capacity must be the actual affected, i.e. it is not constrained. Multiple-output activities are dealt with using substitution. The modelling principles are comprehensively described in Weidema et al. (2009) and Weidema (2003).

Table 12: General modelling approach.

Is it stated which modelling approach is used in the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
No.	No. Attributional and consequential modelling approaches are mentioned, but it is not specified which one is used.	Yes – consequential modelling.	Yes – consequential modelling.

Carbon stocks and land use changes

It is evident that removing wood from forests for paper manufacturing affects the carbon stock in the forests. It is also evident, that paper stores carbon until the carbon in the paper reacts with oxygen (combustion or decomposition) where the carbon is released - mainly as CO_2. None of the four studies takes into account the effect of carbon removal from forests and carbon storage in products.

A change in demand for paper will cause a change in demand for pulp wood. This will change the demand for land suitable for forestry, which is likely to involve changes in the carbon stock and associated CO2 emissions. The mechanisms behind these emissions are often referred to as indirect land use changes (iLUC). None of the four studies takes into account the effect of iLUC.

4.2 Life cycle inventory (LCI)

This section describes and compares the data and modelling in the four reviewed LCA studies.

Life cycle inventory data quality in general: background data

All studies make use of secondary data for accounting for upstream and downstream emissions outside the explicitly modelled foreground system. Examples hereof are emissions from electricity production, manufacturing of equipment (e.g. PC), paper production, recycling/incineration/landfill of paper waste etc.

According to ISO 14044 on LCA, comparative LCA studies which are intended to be disclosed to the public shall include a specification of data quality requirements and an evaluation of data quality. Further, the life cycle interpretation shall include an evaluation of consistency and completeness.

Table 13: Data quality of the life cycle inventory data for the background system.

What are the most used data sources for LCI data? Is it consistent?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Mainly references to external stand-alone studies. The different data sources are probably all based on different years, completeness, geographical regions, modelling assumptions and representativeness.	Background data are primarily from ecoinvent v1.2. But many other LCI-datasets have also been used. E.g. STFI-Packforsk, GaBi, LBP University of Stuttgart. There is no information on consistency between ecoinvent and other LCI data.	Background data from the EASEWASTE waste LCA software. There is no information on consistency between the used LCI datasets.	Background data from the GaBi-EDIP and the ecoinvent databases. There is very limited information on the consistency between two databases.
No specification of data quality requirements nor evaluation of data quality, consistency, and completeness.	No specification of data quality requirements nor evaluation of data quality, consistency, and completeness.	No specification of data quality requirements nor evaluation of data quality, consistency, and completeness.	Sparse information on data quality. No evaluation of data quality, consistency, and completeness.

It appears from the information above that neither the studies report on data quality requirements nor an evaluation of data quality, consistency, and completeness. Data quality may have been evaluated internally but no information about this is made available in the reports.

Modelling of electricity production

All studies have identified electricity to be a hotspot, i.e. a major source of impacts. This is especially the case for the electronic communication, where electricity for data transfer and reading is an important contributor to impacts. Obviously, the impacts related to electricity production are highly dependent on the source of the electricity (coal, gas, hydro, nuclear, wing etc.) and the mix of sources. The choice of electricity mix is often related to the modelling approach (consequential versus attributional), see text next to **Table 12**. The applied electricity mixes in the studies are described in the following table.

Table 14: Electricity mix.

Which electricity mix is assumed in the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Paper production: Swedish average. Other activities: Nordel average (DK, SE, NO, FI, IS).	Elaborated European average.	Coal based.	Coal based.

The specified electricity mixes in the table above only relate to the applied electricity mixes in the modelled foreground system. However, when the studies link to background/database data for the production of equipment, paper production, printing ink, recycling etc., all of them adopt the electricity mix in these data. This means that different electricity mixes are used for the modelled foreground and background systems. Due to this inconsistency, the proportion between the contributions from foreground data and background data may skewing the results. The databases linked to are typically using national/regional average electricity mixes. And further, the electricity use in the background system is regarded as being highest for the printed communication. Therefore, the Sanchez and Møller (2011) and Schmidt and Kløverpris (2009) studies which both apply non-average electricity mixes (with higher impact than average) in the foreground system are likely to underestimate the impact from printed communication more than electronic communication.

The identification of coal as the marginal source of electricity is regarded as doubtful. Looking at energy policies and developments in the electricity mix in Denmark over the last decade (coal share is decreasing), it is high questionable whether marginal electricity can be identified as being coal based. It is more likely that the marginal source of electricity is based on wind and biofuels. The issue of identifying marginal electricity in consequential life cycle inventory modelling is further discussed in Schmidt et al. (2011).

Modelling of paper production

All studies point out the production of paper (including upstream effects) as being a hotspot in the life cycle of printed communication. Therefore, the modelling of paper production in the different studies has been assessed.

Table 15: Modelling of paper production.

How is paper manufacturing modelled? And is the data quality assessed?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Refers to literature data (name of paper manufacturer). Forestry is excluded.	Refers to process in ecoinvent (Newsprint DIP containing) and documents some metadata.	No description of LCI data. Refers to process name in EASEWASTE. LCI data on paper production in EASEWASTE cannot be viewed anywhere.	Refers to ecoinvent data for 'woodfree uncoated fine paper'.

Two of the studies refer to ecoinvent as data source, while Enroth (2009) uses a reference to an unknown eco-profile of a specific paper manufacturer in Sweden, and Sanchez and Møller (2011) refer to EASEWASTE data, which cannot be reviewed without an EASEWASTE license. No of the studies assess the data quality nor consider if the modelling of paper production is consistent with the modelling of the other parts of the product system.

It is regarded as being highly problematic for all the reviewed studies that the data quality for the modelling of a hotspot of the printed communication is not addressed. To stress the significance of the problem, it can be mentioned that the GHG emissions per kg graphical paper in the ecoinvent v3 database range from 0.8 kg CO2-eq to 2.8 kg CO2-eq (both attributional and consequential results). Variations within this range might be enough to alter the conclusions about the comparative assertions in some of the studies. And since there is no data quality assessment, it is likely that it is rather random where in the interval the studies fall. Actually, the Enroth (2009) study uses 0.43-0.54 kg CO_2-eq./kg book (entire life cycle) which is well outside the range.

The variation in impacts for paper production in the ecoinvent database is related to differences in paper quality. Only Moberg et al. (2009) and Schmidt and Kløverpris (2009) specify which paper type/quality has been

used. No of the studies include further analysis of the effect on the comparative results of different paper qualities.

Modelling of end-of-life of paper

For the printed communication, the impact is influenced by the end-of-life modelling of paper.

Table 16: Modelling of recycling.

How is paper waste recycling modelled? Is the data quality assessed?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
It is not clear how recycling has been modelled?	It is stated that recycling is modelled as closed loop. However, the study assumes that 60% paper waste is recycled (= no impact) while the used data on paper production (Newsprint DIP containing) involves considerably lower content of waste paper. Hence, the modelling of recycling seems to be associated with erroneous modelling.	Modelling follows ISO14044, i.e. includes recycling activity and substituted virgin paper. No description of LCI data. Refers to process name in EASEWASTE. LCI data on paper waste recycling in EASEWASTE cannot be viewed anywhere.	Description of the modelling follows ISO14044, i.e. includes recycling activity and substituted virgin paper. However, for the data used for recycling are from 'Paper, newsprint, DIP containing' (from ecoinvent). This data-set reflects paper production from a mix of wood and waste paper, i.e. not purely recycling. Hence, the modelling of recycling seems to be associated with erroneous modelling.

Table 17: Modelling of paper waste incineration.

How is paper waste incineration modelled? Is the data quality assessed?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
It is not clear how waste incineration has been modelled? It is stated that incineration is with energy recovery, but not how this has been modelled.	Incineration is with energy recovery and the modelling includes substituted heat and electricity.	Incineration with heat and electricity recovery. However, the substituted heat is counterintuitively associated with increased impact (not substituted). This is because the substituted heat is assumed to be produced in CHPs where the co-generated electricity substitutes coal based electricity.	Incineration with heat and electricity recovery. But recovered heat is not included in the modelling because the substituted heat is assumed to be waste heat.

It appears from the comparisons in **Table 16** and **Table 17** above that the quality of modelling and data for the end-of-life modelling for printed communication is very doubtful for all studies. Generally the studies fail to applying consistent modelling and to assess whether the data quality is sufficient to meet the purposes of the studies.

For two of the studies, the modelling of recycling, somehow counter-intuitively, implies that recycling is not beneficial for the environment, e.g. recycling is associated with GHG emissions – and not avoided GHG emissions. This is the case in the Sanchez and Møller (2011) and the Schmidt and Kløverpris (2009) studies. This part of the underlying influential factors to the overall results in the two studies is not well described in the studies and therefore this surprising (and questionable) mechanism is hidden for most readers. The reason for this mechanism is, that recycling of waste paper use fossil fuels for the reprocessing (heat and electricity) while

the substituted virgin paper to a large extent rely on biogenic sources of energy (residues from the wood for paper production). The problems related to this way of modelling the impacts are associated to the fact that wood is seen as a 'carbon free'/'impact free' source of fuel. If indirect land use changes and manipulation of the carbon stock in the forest were included, this would not be the case, see Schmidt and Brandão (2012). The issue of land consumption by forestry is further discussed in Schmidt et al (2007).

Further, for waste paper incineration two of the studies involve doubtful mechanisms and/or implications. Namely, the Sanchez and Møller (2011) and the Schmidt and Kløverpris (2009) studies. The expected benefits of heat recovery in Sanchez and Møller (2011) are actually not benefits. This is because it has been assumed that heat generation in Copenhagen is associated with negative impacts – and when incineration substitutes something with negative impacts, then these impacts become positive. The negative impacts related to heat generation are caused because the heat is co-generated with electricity that substitutes coal based (marginal) electricity. As described in the text under **Table 14**, the identification of coal as the marginal source of electricity in Denmark is doubtful.

Summarising, the modelling of end-of-life of paper waste in the four studies show impacts of recycling and waste incineration with different signs. The differences are generally not related to differences in impacts but rather differences in modelling assumptions. Problematic issues are identified in all four studies.

4.3 Life cycle impact assessment (LCIA) and Interpretation

This section describes and compares the findings of the reviewed studies.

Table 18: Study conclusions.

What conclusion is reached by the study?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Impact on global warming of a web based electronic teaching aid is approximately 10 to 30 times of the environmental impact of a printed textbook (depending on the low or high energy equipment scenario)	Tablet performs better than web based newspaper (10 min per day reading time) which performs better than printed version. If reading time of 30 minutes per day web based newspaper same impact as printed. Notable impact of the energy used for editorial work. For the tablet e-paper newspaper, the use phase was negligible regarding environmental impact. Burden-shifting from use phase to production and end-of-life for the tablet.	Prevention scenario leads to large savings in all categories, mostly on GHG. No difference between multi- and single-family scenarios observed. When included, impact of viewing online commercials is approx. 50% lower than the impact of printed commercials	Distributing automatically generated documents in the e-Boks system has less impact on the environment than conventional distribution by ordinary mail

Except for Enroth (2009), the studies reach conclusions that are coherent with the study's initial hypothesis. Sanchez and Møller (2011) and Schmidt and Kløverpris (2009) affirm that printed media perform environmentally worse than electronica media. Enroth (2009) reaches the opposite conclusions, and Moberg et al. (2009) affirm that the electronic media performs better than the printed counterpart only at certain conditions (low reading time). Also, the studies identify different processes as the major contributors to the impacts.

It should be noted that the different studies include different impact categories in the LCIA phase. A complete list of the impact categories included is provided in the appendix A. This means that while the Enroth (2009) study is a carbon footprint, the others have a more complex assessment of potential impacts where trade-offs between different impacts are highlighted and eventually addressed by using normalization and weighting steps.

All studies perform an interpretation of results by applying sensitivity analysis and contribution analysis by process. The former is a technique used to determine how much the final result change when a single parameter of the model is changed (i.e. assigned a different value or substituted with another parameter). The latter is a technique to determine the share of the total impact that is attributable to each of the different stage/activity included within the system boundaries, and is essential to identify hot spots and issues of relevance.

Table 19: Sensitivity analysis

What parameters were included in the sensitivity analysis?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Low and high energy equipment scenario (laptop and LCD screen)	Including infrastructure for electronic distribution, ink production, print of web newspaper, different reading times, different equipment (high and low energy use PC); number of readers per copy; lifetime of electronic devices; multi-use of electronic devices; electricity source.	Saturated market of recycled paper (no substitution of virgin paper but recycled paper); alternative use of the internet to check for commercials online; timber as limited resource; marginal gas electricity production; ink consumption reduced by 68%.	Printing frequency; recycling rates of paper; viewing time; energy consumption of IT equipment.

All studies include sensitivity analyses. It is interesting to observe that all studies recognize the source of electricity and the reading time as two critical parameters.

Table 20: Contribution analysis

What are the processes that most largely contribute to the overall impact?			
Enroth (2009)	**Moberg et al. (2009)**	**Sanchez and Møller (2011)**	**Schmidt and Kløverpris (2009)**
Printed: pulp and paper production (50%) and printing (35%).	**Printed:** newsprint production followed by printing (or by distribution in the Swedish scenario, due to higher diesel use).	Avoided newspaper production (60% of savings). Within this stage, paper production has 80% share of impact for non-tox categories, whereas ink production has 80% share of impact for toxic categories.	**Printed:** envelopes production followed by paper production (sum is 70% of impacts).
Electronic: use (44%) and computer production (38%).	**Electronic:** energy for reading, Editorial work and PC and screen production, incineration for tox categories. **Tablet:** e-paper production.		**Electronic:** viewing of e-Boks documents (use stage, 90% of impacts) for GHG emissions.

All studies seem to agree that production of paper is the process with largest contribution to the impacts in case of printed communication, whereas energy use for reading and production of computers (when included) are the largest contributors for electronic communication. These seem sound results considered the initial problem formulation of the studies.

5 Conclusions

The review of the four comparative LCA studies of printed and electronic communications revealed a number of problematic issues in the studies. The main findings are highlighted below.

Problems related to lack of completeness:

- No studies include the temporal effects on carbon stocks from the harvesting of wood in forests.
- No studies include indirect land use changes.
- Not all studies include the production of infrastructure (internet, servers, PCs etc.).

Problems related to comparability/functional unit:

- Most of the studies assume that there is a 1:1 substitutability between reading time for 1 page printed and 1 page electronic communication. This may not always be the case. Only one of the studies provide empirical evidence to substantiate that the compared systems are comparable. For the other studies, it is highly doubtable whether the compared systems actually provide the same function, i.e. that they are comparable.
- Relating to the bullet above, no studies have addressed which activities could be needed in order to achive a fully comparable basis of the compared systems. E.g. printed commercials are delivered right into the target group's physical mailbox, while the electronic commercials are just present somewhere on the internet. It is likely that the efficiency of attracting the target group will be different – the electronic alternative may need to be accompanied by additional activities. These activities, which could include loyalty programs, additional advertising etc., are not considered.
- No of the reviewed studies consider differences in cost of printed and electronic communication. If there are differences, real comparisons can only be made if the rebound effects are included. When this is included, additional impacts are added to the cheapest alternative.

Problems related to the modelling in life cycle inventory:

- End-of-life modelling of waste paper is inconsistent (and in some cases erroneous).
- The assumed electricity mix can have decisive effect on the results – because the electronic communication is associated with a higher electricity use than printed communication.

Problems related to data:

- Generally, no of the studies addressed the issue of data quality. Hence, there is no documentation of how reliable the used data are.
- Reading time for electronic communication is a key parameter – but only one of the studies uses empirical data for that. The general conclusion on this parameter is that the longer the reading time, the smaller the difference between printed and electronic communication, in terms of overall life cycle impact.
- Data for paper production are more or less randomly/non-critical obtained as existing datasets in LCI databases. Data from the ecoinvent v3 database show significant differences between paper types/qualities. This aspect is not addressed in any study. Further, no of the studies evaluates the data quality of these datasets.

We conclude that the four reviewed studies do not give a comprehensive and clear picture of what is the difference in environmental impact of printed and electronic communication. The studies generally show that electronic communication will be associated with smaller impacts on the environment than printed communication when the reading time is short. However, based on the findings in this review, we argue that

more information is needed to conclude how printed and electronic communication perform for different purposes in a comparative LCA.

It should be noted that the current critical review has analysed only four comparative LCAs of printed and electronic communication. Other studies can be identified on the same topic (Arushanyan et al., 2014; Bull and Kozak, 2014; Hischier and Reichart, 2003). These were not included in the review presented here.

6 References

Arushanyan Y, Ekener-Petersen E, Finnveden G (2014). Lessons learned – Review of LCAs for ICT products and services. Computers in Industry 65, 211-234.

Bull J G, Kozak R A (2014). Comparative life cycle assessments: The case of paper and digital media. Environmental Impact Assessment Review 45, 10-18.

Corominas L., Foley J, Guest J S, Hospido A, Larsen H F, Morera S, Shaw A (2013). Life cycle assessment applied to wastewater treatment: State of the art. Water Research 47, 5480-5492.

Enroth M (2009), Environmental impact of printed and electronic teaching aids, a screening study focussing on fossil carbon dioxide emissions. Advances in Printing and Media Technology, Vol. 36, 2009.

Hischier R, Reichart I (2003). Multifunctional electronic media-traditional media. The International Journal of Life Cycle Assessment 8, 201-208.

ISO 14040 (2006), *Environmental management – Life cycle assessment – Principles and framework*. International Standard Organization (ISO), Geneva.

ISO 14044 (2006), *Environmental management – Life cycle assessment – Requirements and guidelines*. International Standard Organization (ISO), Geneva.

Moberg Å, Johansson M, Finnveden G, Jonsson A (2009), Screening environmental life cycle assessment of printed, web based and tablet e-paper newspaper, Second edition. Reports from the KTH Centre for Sustainable Communications. Stockholm.

Pizzol M, Weidema B P, Brandão M, Osset P (2014). Monetary valuation in Life Cycle Assessment: a review. Journal of Cleaner Production, available online 19, september 2014.

Sanchez V M and Møller J (2011), LCA on the prevention of unsolicited mail in the Vestforbrænding municipalities. DTU Environment. Kgs. Lyngby.

Schmidt J H, Holm P, Merrild A, Christensen P (2007). Life cycle assessment of the waste hierarchy – A Danish case study on waste paper. Waste Management 27(2007):1519‐1530

Schmidt A and Kløverpris N H (2009), Environmental impacts from digital solutions as an alternative to conventional paper-based solutions. e-Boks.

Schmidt J H, Merciai S, Thrane M, Dalgaard R (2011). Inventory of country specific electricity in LCA – Consequential and attributional scenarios. Methodology report v2. 2.‐0 LCA consultants, Aalborg, Denmark. http://lca-net.com/p/212

Schmidt J H, Brandão M (2013). LCA screening of biofuels – iLUC, biomass manipulation and soil carbon. This report is an appendix to a report published by the Danish green think tank CONCITO on the climate effects from biofuels: Klimapåvirkningen fra biomasse og andre energikilder, Hovedrapport (in Danish only). CONCITO, Copenhagen. http://lca-net.com/p/227

Sonnemann G and Vigon B (eds.) (2011), Global Guidance Principles for Life Cycle Assessment Databases. UNEP SETAC Life Cycle Initiative. http://www.unep.fr/shared/publications/pdf/DTIx1410xPA-GlobalGuidancePrinciplesforLCA.pdf

Weidema B P (2003), Market information in life cycle assessment. Environmental Project No 863. Danish Environmental Protection Agency, Copenhagen. http://www.miljoestyrelsen.dk/udgiv/Publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf

Weidema B P, Ekvall T, Heijungs R (2009), *Guidelines for applications of deepened and broadened LCA*. Deliverable D18 of work package 5 of the CALCAS project. http://fr1.estis.net/includes/file.asp?site=calcas&file=7F2938F9-09CD-409F-9D70-767169EC8AA9

Thiesen J, Christensen T S, Kristensen T G, Andersen R D, Brunoe B, Gregersen T K, Thrane M, Weidema B P (2008), Rebound effects of price differences. International Journal of Life Cycle Assessment 13(2):104 114.