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Exploring the Effects of ICT on Environmental Sustainability:

From Life Cycle Assessment to Complex Systems Modeling

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Title: Exploring the Effects of ICT on Environmental Sustainability: From Life Cycle Assessment to Complex Systems Modeling

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Abstract

The production and consumption of information and communication technology (ICT) products and services continue to grow worldwide. This trend is accompanied by a corresponding increase in electricity use by ICT, as well as direct environmental impacts of the technology. Yet a more complicated picture of ICT's effects is emerging. Positive indirect effects on environmental sustainability can be seen in substitution and optimization (enabling effects), and negative indirect effects can be seen in additional demand due to efficiency improvements (rebound effects).

A variety of methods can be employed to model and assess these direct and indirect effects of ICT on environmental sustainability. This doctoral thesis explores methods of modeling and assessing environmental effects of ICT, including electronic media. In a series of five studies, three methods were at times applied in case studies and at others analyzed theoretically. These methods include life cycle assessment (LCA) and complex systems modeling approaches, including System Dynamics (SD) and agent-based (AB) modeling.

The first two studies employ the LCA approach in a case study of an ICT application, namely, the tablet edition of a Swedish design magazine. The use of tablets has skyrocketed in recent years, and this phenomenon has been little studied to date. Potential environmental impacts of the magazine's tablet edition were assessed and compared with those of the print edition. The tablet edition's emerging version (which is marked by a low number of readers and low reading time per copy) resulted in higher potential environmental impacts per reader than did the print edition. However, the mature tablet edition (with a higher number of readers and greater reading time per copy) yielded lower impacts per reader in half the ten impact categories assessed.

While previous studies of electronic media have reported that the main life-cycle contributor to environmental impacts is the use phase (which includes operational electricity use as well as the manufacture of the electronic device), the present study did not support those findings in all scenarios studied in this thesis. Rather, this study found that the number of readers played an important role in determining which life-cycle phase had the greatest impacts. For the emerging version, with few readers, content production was the leading driver of environmental impacts. For the mature version, with a higher number of readers, electronic storage and distribution were the major contributors to environmental impacts. Only when there were many readers but low overall use of the tablet device was the use phase the main contributor to environmental impacts of the tablet edition of the magazine.

The third study goes beyond direct effects at product- and service-level LCAs, revisiting an SD simulation study originally conducted in 2002 to model indirect environmental effects of ICT in 15 European countries for the period 2000-2020. In the current study, three scenarios of the 2002 study were validated in light of new empirical data from the period 2000–2012. A new scenario was developed to revisit the quantitative and qualitative results of the original study. The results showed, *inter alia*, that ICT has a stimulating influence on total passenger transport, for it makes it more cost- and time-efficient (rebound effects).

The modeling mechanism used to represent this rebound effect is further investigated in the fourth study, which discusses the feedback loops used to model two types of rebound effects in passenger transport (direct economic rebound and time

rebound). Finally, the role of systems thinking and modeling in conceptualizing and communicating the dynamics of rebound effects is examined.

The aim of the fifth study was to explore the power of systems modeling and simulation to represent nonlinearities of the complex and dynamic systems examined elsewhere in this thesis. That study reviews previous studies that have compared the SD and AB approaches and models, summarizing their purpose, methodology, and results, based on certain criteria for choosing between SD and AB approaches. The transformation procedure used to develop an AB model for purposes of comparison with an SD model is also explored.

In conclusion, first-order or direct environmental effects of ICT production, use, and disposal can be assessed employing an LCA method. This method can also be used to assess second-order or enabling effects by comparing ICT applications with conventional alternatives. However, the assessment of enabling effects can benefit from systems modeling methods, which are able to formally describe the drivers of change, as well as the dynamics of complex social, technical, and environmental systems associated with ICT applications. Such systems methods can also be used to model third-order or rebound effects of efficiency improvements by ICT.

Keywords: Information and communication technology (ICT), sustainability assessment, electronic media, tablet, print media, magazine, Internet, energy, environmental impact, life cycle assessment (LCA), System Dynamics, agent-based modeling, differential equations, simulation modeling, complex and dynamic systems modeling

Sammanfattning

Den ökande produktionen och konsumtionen av produkter och tjänster inom informations- och kommunikationsteknik (IKT) leder till en ökning av den globala elanvändningen samt direkta miljökonsekvenser kopplade till IKT. Men IKT har även indirekta miljömässiga effekter. Dessa kan vara positiva till exempel genom substitutions- och optimeringseffekter eller negativa genom att till exempel ge upphov till ytterligare efterfrågan på grund av effektivisering (så kallade reboundeffekter).

Olika metoder kan användas för att modellera och bedöma både direkta och indirekta effekter av IKT. Syftet med denna avhandling är att undersöka metoder för modellering samt att studera miljöeffekter av IKT och elektronisk media med hjälp av livscykelanalys (LCA) och även modellering av komplexa och dynamiska system, samt simuleringsteknik, så som System Dynamics (SD) och agentbaserad (AB) modellering. Avhandlingen omfattar fem artiklar (artikel I-V).

Artikel I & II beskriver resultaten från en fallstudie där miljöeffekter kopplade till en svensk tidskrift studeras med LCA. Tidskriftens version för surfplatta samt motsvarande tryckta version studeras och jämförs.

Artikel III går ett steg vidare från produktnivåns LCA. Artikeln återkopplar till en SD simuleringsstudie som ursprungligen genomfördes under 2002. Simuleringsstudien gällde framtida miljöeffekter av IKT i 15 europeiska länder med tidspespektivet 2000-2020. I artikeln valideras tre scenarier från simuleringsstudien med hjälp av nya empiriska data från 2000-2012 och ett nytt scenario modelleras. Kvantitativa och kvalitativa resultat från den ursprungliga studien diskuteras. Till exempel visar artikel III att IKT har en stimulerande effekt på den totala persontrafiken genom att göra den mer kostnads- och tidseffektiv (reboundeffekt).

Modelleringsmekanismen som används för att representera denna reboundeffekt diskuteras vidare i artikel IV. Artikeln belyser och diskuterar den återkopplingsslinga (feedback-loop) som används för att modellera två typer av reboundeffekter kopplade till persontrafik (direkt ekonomisk rebound och tidsrelaterad rebound) samt jämför med en tidigare studie. Artikel IV behandlar också den roll systemtänkande och modellering kan spela i konceptualisering och kommunikation av reboundeffekters dynamik.

För att ytterligare undersöka systemmodelleringens och simuleringens möjligheter att representera icke-linjära komplexa och dynamiska system (exempel på sådana diskuteras i artikel III och IV), sammanställer artikel V tidigare studier som jämför SD och AB-metoder och -modeller. Studiernas mål och metod summeras och resultaten med avseende på vilka kriterier som presenteras för att välja mellan SD och AB sammanställs. Även processen för att omvandla en befintlig SD-modell till en AB-modell beskrivs.

Avhandlingens slutsats är att LCA och systemmodelleringsmetoder kan vara användbara för att studera IKTs direkta effekter så väl som indirekta effekter på miljön.

Nyckelord: Informations- och kommunikationsteknik (IKT), hållbarhetsbedömning, elektroniska media, surfplatta, tryckta media, tidskrift, Internet, energi, miljöpåverkan, simulering, differentialekvationer, modellering av komplexa och dynamiska system, System Dynamics, livscykelanalys (LCA), agentbaserad modellering

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Stockholm, July 2015
Mohammad Ahmadi Achachlouei

List of papers

PAPERS INCLUDED IN THE THESIS

Paper I	Ahmadi Achachlouei, Mohammad, Åsa Moberg and Elisabeth Hochschorner. "Life cycle assessment of a magazine, Part I: Tablet edition in emerging and mature states." *Journal of Industrial Ecology* (2015) DOI: 10.1111/jiec.12227
Paper II	Ahmadi Achachlouei, Mohammad and Åsa Moberg. "Life cycle assessment of a magazine, Part II: A comparison of print and tablet editions." *Journal of Industrial Ecology* (2015) DOI: 10.1111/jiec.12229
Paper III	Ahmadi Achachlouei, Mohammad and Lorenz M. Hilty. "Modeling the effects of ICT on environmental sustainability: Revisiting a System Dynamics model developed for the European Commission." *ICT Innovations for Sustainability*, *Advances in Intelligent Systems and Computing* 310 (2015): 449-474.
Paper IV	Ahmadi Achachlouei, Mohammad and Lorenz M. Hilty. "Using systems thinking and System Dynamics modeling to understand rebound effects." *Advances and New Trends in Environmental Informatics: Selected and Extended Contributions from the 28th International Conference on Informatics for Environmental Protection*, Springer Series: *Progress in IS* (2015, accepted).
Paper V	Ahmadi Achachlouei, Mohammad and Lorenz M. Hilty. "System Dynamics vs. agent-based modeling—Comparing models and approaches: A literature review and a transformation procedure." Submitted to the journal *Environmental Modelling & Software*.

Comment on co-authored papers:

Mohammad Ahmadi Achachlouei was responsible for the literature review, data collection, modeling, analysis and writing the main part of Papers I, II, III, IV and V.

RELATED PAPERS NOT INCLUDED IN THE THESIS

Hischier, Roland, Vlad C. Coroama, Daniel Schien and Mohammad Ahmadi Achachlouei. "Grey energy and environmental impacts of ICT hardware." *ICT Innovations for Sustainability*, *Advances in Intelligent Systems and Computing* 310 (2015): 171-189.

Hischier, Roland, Mohammad Ahmadi Achachlouei and Lorenz M. Hilty. "Evaluating the sustainability of electronic media: Strategies for life cycle inventory data collection and their implications for LCA results." *Environmental Modelling & Software* 56 (2014): 27-36.

Ahmadi Achachlouei, Mohammad and Lorenz M. Hilty. "Modelling rebound effects in System Dynamics." *Proceedings of the 28th International Conference on Informatics for Environmental Protection, EnviroInfo*. 2014.

Ahmadi Achachlouei, Mohammad, Åsa Moberg and Elisabeth Hochschorner. "Climate change impact of electronic media solutions: Case study of the tablet edition of a magazine." *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability, ICT4S*. 2013.

Picha Edwardsson, Malin, Mohammad Ahmadi Achachlouei and Åsa Moberg. "Magazine publishing: Editorial process structure and environmental impacts-case study." *Proceedings of the Technical Association of the Graphic Arts, TAGA*. 2012.

Abbreviations

AB	Agent-Based
ABM	Agent-Based Modeling
AOX	Absorbable organically bound halogens
CBA	Cost-Benefit Analysis
CESC	Centre for Sustainable Communications
CLD	Causal Loop Diagram
COD	Chemical oxygen demand
DE	Differential equations
DSLAM	Digital Subscriber Line Access Multiplexer
EC	European Commission
EF	Ecological Footprint
EIA	Environmental Impact Assessment
EIO	Economic Input-Output
EMS	Environmental Management System
EPD	Environmental Product Declaration
ESA	Environmental Systems Analysis
FTE	Full-time employee equivalent
GeSI	The Global E-Sustainability Initiative
GHG	Greenhouse gas
ICT	Information and Communication Technology
IOA	Input-Output Analysis
IP	Internet Protocol
IPTS	Institute for Prospective Technological Studies
ISO	International Organization for Standardization
ITS	Intelligent Transport System
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
MFA	Material Flow Analysis
MIPS	Material Intensity Per Unit Service
ODE	Ordinary differential equations
OECD	The Organisation for Economic Co-operation and Development
PC	Personal Computer
Pkm	Passenger-kilometer
PLCA	Process-based Life Cycle Assessment
SD	System Dynamics
SEA	Strategic Environmental Assessment
SEEA	System of Economic and Environmental Accounting
SETAC	Society of Environmental Toxicology and Chemistry
SFA	Substance Flow Analysis
SFD	Stock/Flow Diagram
SME	Small and Medium-sized Enterprise
TMR	Total Material Requirement
TSP	Total Suspended Particulates

Table of Contents

1. Introduction

1.1. Motivation

The production and consumption of information and communication technology (ICT) products and services continue to grow worldwide (ITU, 2013). This trend is accompanied by growth in electricity use by ICT networks, personal computers (PCs) and data centers, and, in recent years, electricity consumption in all these ICT categories has increased at a higher rate than total worldwide electricity consumption (Van Heddeghem et al., 2014).

In addition to direct energy use, ICT, throughout its whole life cycle, demands energy and entails environmental burdens through resource use and also releases into water, soil, and air (Hischier et al., 2015), such as greenhouse gas (GHG) emissions (Malmodin et al., 2010), exposure to hazardous substances (Williams, 2011) and depletion of material resources (Wäger et al., 2015).

Despite such negative environmental impacts, ICT can have positive effects on environmental sustainability through substitution and optimization effects, as well as transition towards sustainable patterns of production and consumption (Hilty & Aebischer, 2015). Most recently, the *Smarter 2020* report (GeSI, 2012) estimated that the total abatement potential of ICT-enabled solutions in 2020 would be about nine gigatons of carbon dioxide equivalent ($GtCO_2e$), "a saving of about 16.5% of global GHG emissions by 2020" (Laitner, 2015).

However, such macro-level estimates usually do not take into account the rebound effects counteracting ICT-induced progress in resource efficiency, e.g., via stimulating additional demand for the resource being used efficiently (Börjesson Rivera et al., 2014; Gossart, 2015).

A variety of environmental systems analysis methods have been used for environmental sustainability assessment of ICT, ranging from life cycle assessment of ICT products and services (Arushanyan et al., 2014) to material flow analysis of electronic waste (Steubing et al., 2010), and also systems simulation modeling approaches such as System Dynamics to address indirect and rebound effects of ICT (Erdmann & Hilty, 2010; Hilty et al., 2006).

Despite previous studies on direct and indirect effects of ICT on environmental sustainability, there are further questions to be answered. It is still difficult to clearly determine the benefits of ICT solutions in electronic media over their conventional paper-based formats in terms of their environmental impacts. Moreover, due to rapid developments in ICT products and services and continuous changes in patterns of adoption and use of these products and services in society, it is important to provide updated analyses considering new socio-economic and technical developments and to integrate appropriate methods of complex and dynamic systems into the portfolio of environmental sustainability assessment tools in the field of ICT production and consumption.

1.2. Aims of the thesis

The main aim of this doctoral thesis was to explore methods for modeling and assessing environmental effects of information and communication technology (ICT) and electronic media, focusing on life cycle assessment (LCA) and complex systems modeling techniques including System Dynamics (SD) and agent-based (AB) modeling. The thesis consists of this cover essay and five papers.

The main objectives of the studies included in the thesis were to:

- Assess potential environmental impacts of production and consumption of an ICT application from a life cycle perspective and compare its environmental impacts with those of a conventional product system (Papers I and II),
- Explore the dynamic future impact of ICT on environmental sustainability, including direct, indirect and rebound effects of ICT, using a System Dynamics approach (Paper III),
- Investigate the feedback loops used to represent the dynamics of direct rebound effects induced by cost and time efficiency (Paper IV),
- Gain a better understanding of the strengths and weaknesses of two systems modeling techniques, System Dynamics and agent-based modeling, in addressing dynamically complex phenomena (Paper V).

Employing the LCA approach, Papers I and II focused on the case of an ICT application, the tablet edition of a Swedish magazine, where potential environmental impacts of the tablet edition were assessed and compared with those of the print magazine. The specific research questions examined in Papers I and II were: What are the main environmental impacts of the print and tablet editions? What activities give rise to the main environmental impacts for the print and tablet editions? What are the key factors influencing these impacts? What are major data gaps and uncertainties?

Whereas Papers I and II conducted product/service-level analyses, Paper III explored the dynamics of positive and negative impacts of ICT on environmental sustainability at an aggregate level for the region of Europe. This was achieved by revisiting a System Dynamics simulation study performed in 2002 on the future impacts of ICT in 15 European countries in the period 2000-2020. Using new empirical data from 2000-2012, Paper III sought to validate assumptions in three scenarios developed in the original study, developed a new scenario with more realistic input data for the first half of the simulation period and revisited the main quantitative and qualitative results of the original study.

The simulation results in Paper III indicated that ICT has a stimulating influence on total passenger transport by making it more cost- and time-efficient (rebound effect). Paper IV examined the modeling mechanisms representing this rebound effect by comparing the feedback loops used to model two types of rebound effects (direct economic rebound and time rebound) with those used in another study of rebound in passenger transport. Paper IV also examined the contribution of systems thinking and modeling to rebound analysis.

To further investigate the capability of systems modeling in sustainability assessments, Paper V compared the SD and AB approaches in terms of their relationships and appropriateness in different situations. The specific research question examined in Paper V was: How can we reuse the knowledge represented in a given SD model to build AB models representing the same knowledge, but also providing more knowledge which can enhance our exploratory power for a better understanding of systems behavior? To answer this question, the following more detailed research questions were investigated: What are strengths and weaknesses of AB and SD approaches? When is it appropriate to use AB and when SD? Are there any benefits of using one method compared with the other? What types of scenarios can be explored with the AB approach but not with SD? How can a given SD model be transformed into an equivalent AB model? What further actions are needed to obtain an AB model that exploits the strengths of the AB approach? Paper V describes a procedure for building an AB model equivalent to a given SD model and demonstrates the procedure, using the example of the model studied in Paper III, to examine the dynamics of time rebound effects of mobile ICT on passenger transport.

1.3. Outline of the thesis

The dissertation consists of this cover essay and the five papers (Papers I-V) appended. The cover essay summarizes the papers and puts them into context. In Chapter 1 the motivation and overall aim of the thesis and also specific objectives of Papers I-V are described. Chapter 2 provides the background and an overview of the research field. The methods and their application in the current thesis are addressed in Chapter 3. The results of the Papers I-V are summarized in Chapter 4. Chapter 5 discusses the findings and limitations of the research, places the research presented in the thesis in context and makes suggestions for future research. Finally, Chapter 6 presents some general conclusions.

2. Background

This chapter provides background to the studies described in Papers I-V and presents an overview of typologies used to classify ICT effects, a brief introduction to LCA and its use in environmental assessment of ICT, and also a brief introduction to systems modeling and simulation techniques and their application to sustainability assessment.

2.1. Typology of ICT effects

New ICT devices and applications are emerging at high speed and new ways of distributing media content and doing e-business are being developed. For example, recent studies show that although the amount of time the average Swedish person spends on media has changed little during the last 10-20 years (Nordicom-Sverige, 2011b), the number of alternative choices of media products (including both new forms of media, e.g., social media, and conventional media in new forms, e.g., online music streaming) has increased. The younger generation in particular is increasingly spending their time on new electronic media (Nordicom-Sverige, 2011a).

ICT and ICT-based applications such as electronic media can have both positive and negative effects on environmental sustainability (Berkhout and Hertin, 2004; Hilty et al., 2006; Williams, 2011).

When investigating the effects of the development, diffusion and use of ICT on environmental sustainability, various types of effects can be considered. Several typologies have been proposed in the literature:

- A three-order typology introduced by Berkhout and Hertin (2001) in an OECD report has been widely re-used in many studies (with slightly different interpretations): (1) First-order impacts: "direct environmental effects of the production and use of ICTs;" (2) second-order impacts: indirect environmental impacts through the change of "production processes, products, and distribution systems;" and (3) third-order impacts: indirect environmental impacts "through impacts on life styles and value systems" (Berkhout & Hertin, 2001).
- A two-level typology of impacts by Plepys (2002): (1) First, the impacts related to the life cycle of ICT hardware and (2) second, those related to the way the ICT applications are being used.
- A two-order typology by Börjesson Rivera et al. (2014): First-order effects including direct effects and substitution effects; and (2) second-order effects, including re-materialization effects, induction, direct economic rebound effects, indirect economic rebound effects, economy-wide rebound effects, time rebound, space rebound, "learning about production and consumption," "scale effects and learning in production and consumption," changed practices, and transformational rebound effects.
- A four-level typology by Williams (2011) for levels of system interactions between ICT and the environment: (1) The first level of direct impacts for ICT infrastructure and devices; (2) the second level for ICT applications

used to reduce environmental impacts through optimization and substitution; (3) the third level for ICT effects on economic growth and shifting consumption patterns; and (4) the fourth level for systemic effects of ICT on "the info-nano-robotics-bio technological convergence that some believe will transform industry and society" (Williams, 2011).

- Another three-level model by Hilty and Aebischer (2015), as shown in Figure 1, combines the three-order typology of Berkhout and Hertin (2001) with another dimension that distinguishes positive from negative impacts, i.e., "ICT as part of the problem" from "ICT as part of the solution.": (1) The first level addresses the direct effects of production, use, and disposal of ICT products (i.e., life cycle emissions and energy/materials demand), which include environmental costs and are "part of the problem;" (2) the second level refers to enabling effects of ICT applications/services/solutions, including positive effects related to substitution and optimization (efficiency improvement) and negative effects associated with obsolescence (i.e., shorter useful life of another resource due to its incompatibility with the new version of an ICT application); (3) the third level is concerned with systemic effects including positive effects related to transition toward sustainable patterns of production and consumption and negative effects associated with rebound effects and emerging risks.

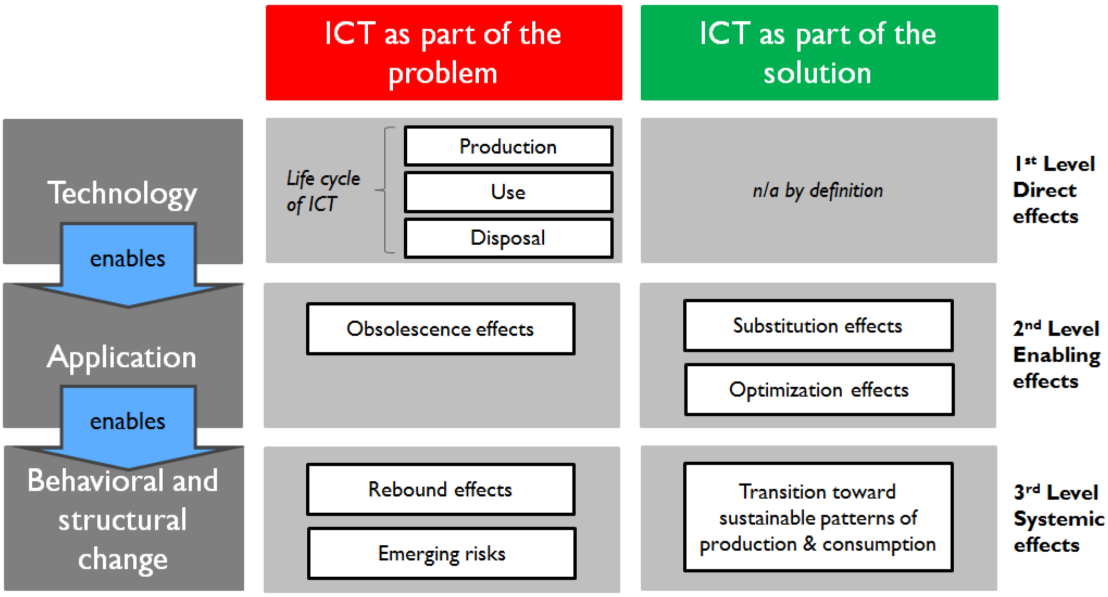

Figure 1. Typology of the effects of ICT on environmental sustainability (adapted from Hilty & Aebischer, 2015).

Rebound effects of ICT are part of indirect effects of ICT, which are addressed in all typologies, termed as second-order effects (Börjesson Rivera et al., 2014) or as third-order effects, as shown in Figure 1 (Hilty & Aebischer, 2015). Rebound effects, defined in energy economics (Berkhout et al., 2000), have become part of the "grey" side of ICT (Plepys, 2002). In recent studies, Börjesson Rivera et al.

(2014) and Gossart (2015) review and discuss various types of rebound effects that can be linked to ICT usage. Direct economic rebound, time rebound, income (or indirect economic) rebound, and economy-wide rebound effects are among these various types of rebound effects. Erdmann and Hilty (2010) provide an abstract causal structure (for the IPTS model which is also investigated in Paper III), as shown in Figure 2, which is basically an interpretation of the definitions of the first-, second-, and third-order effects of ICT in a simplified form. In Figure 2**,** first-order effects on the environment originate from ICT development (production and manufacturing) and use (as well as waste treatment); second-order effects of ICT application services can be modeled using the enabling potential of ICT-based substitution and efficiency, together with the speed at which this potential is realized. The dynamic impacts of ICT originate from the feedback of third-order effects to first- and second-order effects (Erdmann & Hilty, 2010). Börjesson Rivera et al. (2014) emphasize the importance of developing methods which include rebound effects when analyzing the environmental impacts of ICT. Paper IV, an extension of Achachlouei and Hilty (2014a), highlights causal feedback loops and System Dynamics models that are used to model the rebound effects of ICT.

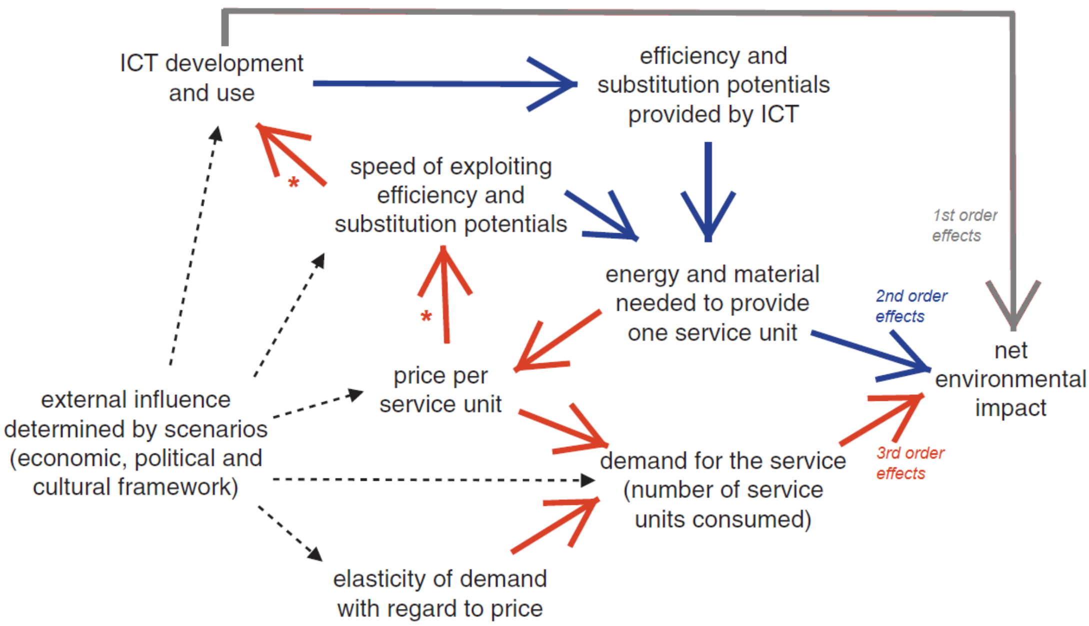

Figure 2. Abstract causal structure to describe the relationship between three types of ICT effects (Erdmann & Hilty, 2010). Colors: Grey for first-order, blue for second-order, and orange for third-order effects. The symbol * on arrows indicates that the dynamic impacts of ICT originate from the feedback of third-order effects to first- and second-order effects.

2.2. Life cycle assessment (LCA)

Life cycle assessment is used to assess the potential environmental impacts[1] and resources consumed throughout a product's life cycle, from raw material extraction, via production and use phases, to waste management (ISO, 2006a).

Papers I-II employed the methodology of life cycle assessment as described in the standard documents ISO 14040 and ISO 14044 (ISO, 2006a, 2006b), and the software SimaPro 7.2.3 (PRé Consultants, 2011).

LCA is an analytical tool in the field of environmental systems analysis (ESA). Other examples of ESA tools in the field include e.g., environmental impact assessment (EIA), material flow analysis (MFA), risk assessment, life cycle costing (LCC), system of economic and environmental accounting (SEEA), and environmental auditing (Finnveden & Moberg, 2005).

The development of LCA dates back to the late 1960s and early 1970s (Guinée et al., 2011). Reviewing the evolution of LCA, Guinée et al. (2011) cite an unpublished study in 1969 on different beverage containers (of the Coca Cola Company) as one of the first studies "quantifying the resource requirements, emission loadings, and waste flows."

LCA, as shown in Figure 3, is performed in four phases: definition of goal and scope, life-cycle inventory (LCI) analysis (definition of the product system, collection of data and calculations of inputs and outputs), impact assessment (including selection of impact categories and classification, selection of characterization methods and characterization, and the optional phases of normalization, grouping and weighting) and interpretation (ISO, 2006a, 2006b). This is an iterative process, during which it is possible to go back to earlier phases and improve the analysis.

The LCI step in the LCA method involves creating an inventory of flows from and to nature caused by a product system. This step can be performed via conventional process LCA (PLCA), economic input-output LCA (EIO-LCA) or a hybrid technique combining the advantages of both PLCA and EIO-LCA (Suh et al., 2004).

[1] It should be noted that LCA measures the *potential* environmental impacts of a given product system, not *actual* environmental impacts. Because this phrase is cumbersome, in most instances I omit the word "potential," referring simply to "environmental impacts." It should be borne in mind that this language is shorthand and indeed refers to potential environmental impacts.

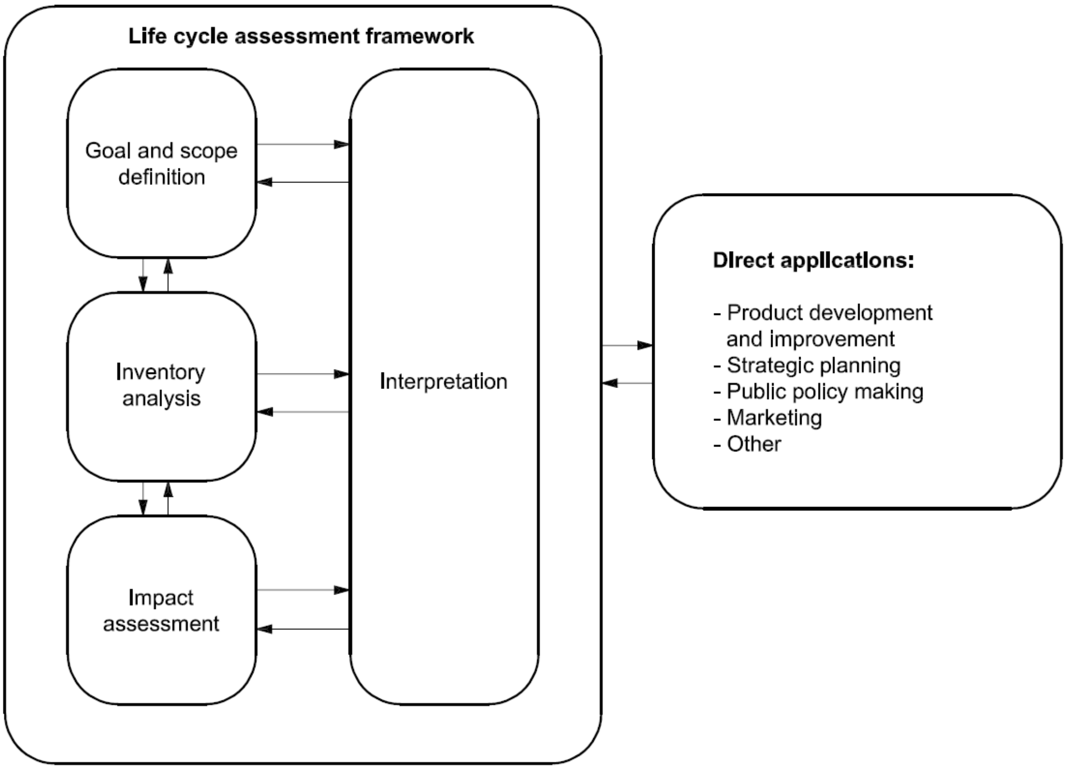

Figure 3. Phases of an LCA (ISO, 2006a).

2.3. LCA of ICT and electronic media: An overview

Life cycle assessment has been widely employed in environmental assessment of ICT and electronic media.

LCA of ICT. When comparing ICT-based solutions with their conventional counterparts, in order to avoid shifting problems from one stage and/or region to another, it is best to conduct a full LCA for a well-defined function of the products being compared (Weber et al., 2010). Arushanyan et al. (2014) reviewed the LCAs of ICT products and services and found that some consumer products, such as computers and TVs, have been studied more than other consumer products, such as game consoles and TV peripherals, and business products, such as network-related products. Among ICT life cycle activities, they found that the manufacturing and use phase have the highest impact, noting "use phase seems to be the predominant in energy consumption and global warming for some ICT products but for others, especially energy efficient, low weight products, manufacturing may dominate" (Arushanyan et al., 2014).

LCA of electronic media. Environmental impacts of electronic media can be compared with those of print media. Previous studies on energy use and environmental impacts of print and electronic media have shown there is no one answer as to which type of product is preferable from an environmental standpoint (Arushanyan et al., 2014; Bull & Kozak, 2014; Enroth, 2009; Hischier & Reichart, 2003; Kronqvist et al., 2010; Moberg et al., 2011; Moberg et al., 2010). These studies include media such as daily newspapers, novels, scholarly books, and magazines, as well as electronic versions read from desktop computers and e-ink tablet devices (e-readers). Previous studies have employed a life cycle approach, yet content production has only been estimated or has not been included at all except in a few studies such as that by Arushanyan et al. (2014), which identifies the high contribution of content production to total GHG emissions in an LCA of a Finnish online newspaper with rather few readers (emerging state). Picha et al. (2012) provide a detailed analysis of sub-processes in content production and their GHG emissions.

In a recent study, Coroama et al. (2015a) analyzed electronic media and their effects on environmental sustainability with a life cycle perspective and found that while some application areas of electronic media (such as videoconferencing) can be an energy-efficient substitute to the conventional approaches (such as long-distance travel), certain uses of electronic media (e.g., e-newspapers and e-magazines) may just add new environmental costs on top of existing activities (e.g., paper-based newspapers and magazines), instead of replacing them. Discussing the dematerialization potential of electronic media, Coroama et al. (2015a) concluded that "[t]he availability of small, energy-efficient devices being used as electronic media does not guarantee dematerialization. The overall resource use and emissions throughout the life cycle of the media product systems and, more importantly, at the macro level of total global production and consumption need to be considered. To achieve the dematerialization potential of new electronic media solutions, their efficiency needs to be combined with sufficiency; thus additional measures are necessary to turn the dematerialization potential of electronic media into environmental relief" (Coroama et al., 2015a).

LCA of electronic and print magazines. Both print and electronic versions of a typical Swedish magazine were assessed in a previous study (Kronqvist et al., 2010). In that study, however, the electronic version was read from a desktop computer, not from a tablet. Kronqvist and colleagues (2010) found that the climate impacts of the print and electronic versions were of the same order of magnitude. They also found that user practices were important for the resulting environmental impacts. User practices are highlighted in other comparative environmental assessments of media products, e.g., Moberg et al. (2011). The development of new electronic devices is rapid and boundless. New tablet devices are less energy-demanding than computers, and the environmental impacts related to their manufacture can be assumed to be generally lower. It is therefore of interest to learn more about the possibilities for better environmental performance for media on tablets. To complement the studies conducted to date and to learn more about the environmental impacts of print and electronic media, Papers I-II in this thesis investigated the life cycle impacts of magazines in print and tablet editions, the latter of which is read from a tablet with an LCD screen, the most common type of tablet today. Papers I-II also examined content production in more detail than previous assessments.

2.4. Systems modeling and simulation

Computer-based modeling and simulation of complex and dynamic systems have been widely used in scientific research, including environmental sustainability assessments (Kelly et al., 2013). Modeling and simulation encompass a range of techniques such as System Dynamics, agent-based modeling, discrete-event simulation, Monte Carlo simulation, and gaming modeling and simulation. As shown in Figure 4, a modeling and simulation project starts with the recognition of a problem situation, builds a conceptual model in an iterative process (through formulation of modeling objectives, scope, level of detail of the model content and input data requirements) and then continues with model coding, data collection, experimentation and interpretation of simulation results, and informing decision-making processes (and possibly implementation of decisions in the real system, changing the actual nature of the problem situation).

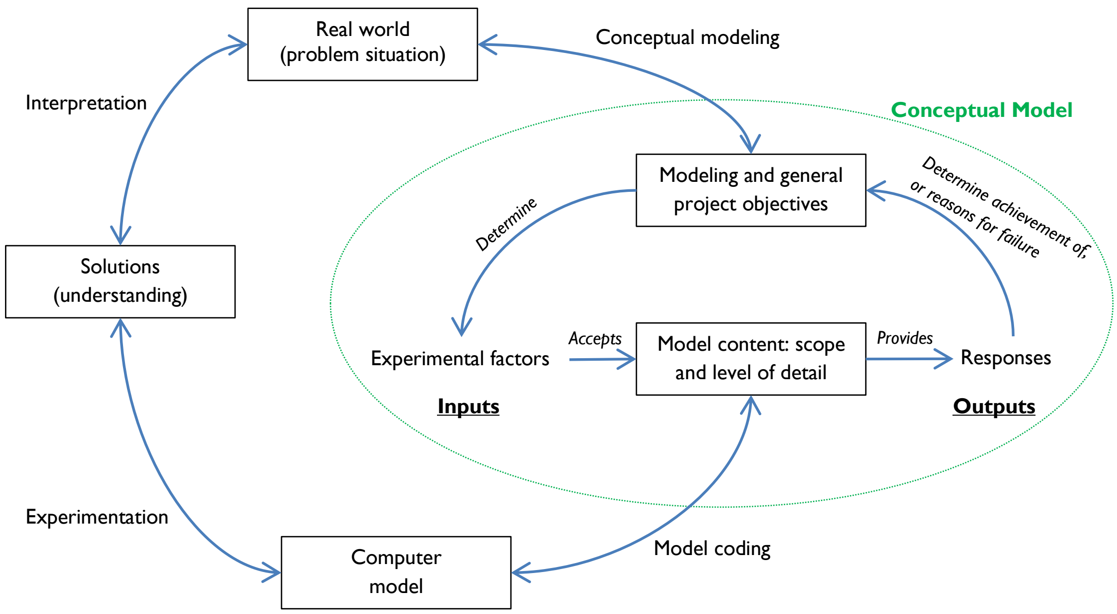

Figure 4. Phases of a modeling and simulation project (adapted from Robinson (2008)). Double-headed arrows indicate the interplays between the key elements.

2.4.1. Basic definitions

The key terminology used in modeling and simulation is as follows:

- **Model.** A model can be defined as a system S' that an observer uses in the place of a system S in order to answer questions of interest about S.
- **Simulation.** The method of simulation (as opposed to the analytical use of models) is a specific way of using S' to generate answers, namely experimentation.
- **Simulation experiment.** In a simulation experiment, the model is exposed to experimental conditions (called experimental factors in Figure 4), represented by the simulation input data, and shows an observable reaction by producing simulation output data.
- **Simulation model.** A simulation model is a model specifically designed to be used for simulation.

2.4.2. What is System Dynamics?

The System Dynamics Society introduces SD as follows: "System dynamics is a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality" (see Richardson (2011) for an overview of SD and suggestions for further reading). Jay Forrester, the founder of SD, points out three key principles in this approach: feedback control theory, understanding the decision-making process, and the use of computer-based technologies to develop simulation models (Forrester, 1961, p. 464).

Two layers of SD can be distinguished:

- **Qualitative SD**, at a systems thinking level, including stock/flow diagrams (SFD) and causal loop diagrams (CLD) (Lane, 2008), usually combined with group model building (e.g., Laurenti et al., 2014) or participatory modeling (e.g., Mendoza & Prabhu, 2006). In addition, some consider SD a world view or a paradigm (Sterman, 2002).
- **Quantitative SD**, which is grounded in control theory and the modern theory of nonlinear dynamics (Sterman, 2002). The mathematical foundation of SD as a computer simulation model is a system of coupled, nonlinear differential equations, $d\mathbf{x}(t)/dt=\mathbf{f}(\mathbf{x}, \mathbf{p})$, where $\mathbf{x}$ is a vector of stocks (levels or state variables), $\mathbf{p}$ is a set of parameters and $\mathbf{f}$ is a nonlinear vector-valued function (Richardson, 2013).

2.4.3. What is agent-based modeling?

Agent-based (AB) models provide modeling constructs to represent the interactions between autonomous entities in a system representing most often groups of humans, but also of animals, bacterial cells, cells composing the human immune system or biophysical entities such as water (Kelly et al., 2013). By modeling individual agents and their interactions, emergent system behaviors that are not explicitly programmed into the models are often observed (Macal et al., 2013). The interactions of agents with each other and the environment result in behavior emerging at the system level (see Bonabeau (2002) for an overview of AB modeling in human systems; Macal & North (2010) for a brief tutorial on AB modeling; Hare & Deadman (2004) for an overview of AB modeling in environmental modeling; and Heath et al. (2009) for a survey of AB modeling practices). A synonym for AB modeling would be microscopic modeling, and an alternative to AB modeling would be macroscopic modeling (Bonabeau 2002).

A typical AB model has three elements (based on Macal & North (2010)):

1. A set of agents with attributes or state variables and behavior rules.
2. A set of agent relationships and methods of interaction: An underlying topology of connectedness defines how and with whom agents interact.
3. The agents' environment: Agents interact with their environment in addition to other agents.

2.5. Systems modeling and simulation for sustainability assessment

Systems modeling and simulation approaches have been applied in sustainability assessments for purposes such as prediction, forecast, policy making under uncertainty and social learning, as well as theory building, system understanding and experimentation (Kelly et al., 2013). Such applications cover a variety of research areas, including integrated assessment, environmental modeling, transition modeling, and social-ecological modeling (Halbe et al., 2015; Schlüter et al., 2013).

Looking for examples of systems modeling and simulation to study the effects of ICT on environmental sustainability in Paper III, we only found the simulation study by Hilty et al. (2006), which is revisited in Paper III and discussed in Paper IV.

This section presents an overview of studies employing systems modeling and simulation for sustainability assessment purposes, in order to provide a general picture of the types of application areas and analyses conducted in the field.

2.5.1. System Dynamics for sustainability assessment: An overview

System Dynamics has been used for sustainability assessment purposes. Examples from the literature are presented in this subsection.

An outstanding example is the SD model described in "*The Limits to Growth,*" a book first published in 1972 that uses computer modeling to estimate the future ecological burden of human society if it continued to consume limited natural resources (Meadows et al., 2004).

Hilty et al. (2006) modeled a three-level typology of ICT using a SD approach in combination with scenario techniques and expert consultations. This prospective study (which is revisited in Paper III and some of its feedback mechanisms are discussed in Paper IV) assessed the impact of ICT on environmental sustainability in the European Union (EU) within a time span up to 2020 (the SD model is described in the next section).

Musango et al. (2012) propose a SD approach to technology sustainability assessment with a focus on policy interventions for renewable energy developments in a case study in a province of South Africa. They use a SD model combined with some scenarios to analyze the outcome of proposed biodiesel production development on sustainability indicators and to compare dynamic consequences that may result from such a development considering the associated policies and decisions.

Xu and Coors (2012) employ SD simulation modeling (combined with GIS and 3-D visualization)[2] in sustainability assessment of urban residential development in the Stuttgart region of Germany. They use SD to better capture the impacts caused by local-level urban activities at a broader scale and to "quantitatively investigate the developmental tendency" of the sustainability indicators (Xu and Coors, 2012).

Videira et al. (2012) use qualitative SD combined with a participatory modeling approach to support scoping stages of an integrated sustainability assessment process in mapping maritime sustainability issues in Portugal. During participatory modeling workshops in that study, "stakeholders deliberated on maritime problems and constructed causal loop diagrams, identifying feedback structures and voting on leverage points to intervene in the system" (Videira et al., 2012).

Zhang et al. (2013) built a qualitative SD (or systems thinking) model including sustainability assessment elements. The conceptual model is embedded in a system dynamics model, with substructures presented at the operation level and the shop floor level.

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[2] GIS: Geographic Information Systems; 3-D: a three-dimensional form

2.5.2. Agent-based modeling for sustainability assessment: An overview

Agent-based modeling has been used for sustainability assessment purposes. Examples from the literature are presented in this subsection.

Drawing upon urban economics and environmental science and planning, Zellner et al. (2008) present a generic AB model called the Urban Sustainability Assessment Framework for Energy to model land use decisions and consequent energy consumption and pollution dynamics in an urban system. They justify their choice of AB modeling over other spatial modeling tools by noting that the analysis of drivers and behaviors associated with the interaction of heterogeneous landscapes and actors operating at different spatial and temporal scales is better performed using AB modeling because it supports "explicit representation of socio-economic, political and natural processes in space and time and the feedback mechanisms connecting them" (Zellner et al., 2008).

Xu et al. (2009) employ an AB approach to explore environmental impacts associated with an e-commerce market. They use psychological theories to model the behavior of consumers as agents and their choices of different methods to buy a book (including conventional bookstores, e-commerce, and self pick-up) and then to assess the environmental consequences of a shift from bookstore purchase to e-commerce under various scenarios, providing insights into the development and implementation of more sustainable policies and practices.

Tabara et al. (2008) describe an integrated sustainability assessment of water systems (the case of the Ebro River Basin in Spain) employing AB modeling and gaming tools through implementation of visioning and experimenting exercises involving stakeholders. They conclude that the use of such tools helps "to represent complexity, to learn how conflict and collaboration between agents can be addressed, and to explore the roles played by power regimes, institutional rules, and culture in constraining or enhancing transition in the water domain" (Tabara et al., 2008).

Astier et al. (2012) in their critical analysis of sustainability assessment of Small Farmer Natural Resource Management Systems, use AB modeling and simulation modeling (together with role play games) to support participatory processes.

2.5.3. Combined use of systems modeling techniques

Hybrid use of SD and AB modeling for sustainability assessment

Hybrid simulation models, which involve the use of multiple systems modeling and simulation approaches, are becoming more common in modeling complex systems. Hybrid models can combine both SD and AB modeling in various ways (Lättilä et al., 2010; Swinerd & McNaught, 2012).

For example, in order to assess transitions to sustainable mobility in the UK (as part of the EU MATISSE project and part of an integrated sustainability assessment), Köhler et al. (2009) develop an AB model based on the multi-level perspective theory. They define two levels of agents: a large number of simple agents (consumers) and a small number of complex agents (the regime and niches). To model the complex agents, which are subsystems within society, Köhler et al. (2009) use a SD structure.

Luisa et al. (2013) combine systems simulation (including SD and AB modeling) techniques with participatory modeling to assess the socio-environmental sustainability of a wetland restoration program in Australia. They employ simulation modeling to identify the main elements and relationships of the wetland system, to map plausible scenarios for sustainable development and to identify sustainability indicators for the wetland's socio-environmental system (Luisa et al., 2013).

Scenario analysis combined with systems modeling

Scenario analysis, as a technique used in futures studies (Börjeson et al., 2006), can be combined with systems modeling and simulation in sustainability assessment studies (see e.g., Luisa et al., 2013; Musango et al., 2012; Österblom et al., 2013). In the IPTS study revisited in Paper III, scenario analysis together with SD is used to explore the future impact of ICT on environmental sustainability (Erdmann & Hilty, 2010).

While qualitative approaches to scenario analysis, such as narratives, offer "texture, richness and insight," quantitative approaches, such as systems modeling offer "structure, discipline and rigor" (Swart et al., 2004). Systems modeling can be used in forward-looking scenario analysis to quantify initial conditions and drivers of change and to model socio-economic developments and the environmental changes they cause (Swart et al., 2004).

3. Methods

This chapter briefly describes how LCA and systems modeling and simulation were employed in the present thesis.

3.1. How LCA is applied in Papers I-II

LCA was used in Papers I and II, as briefly summarized in this subsection. Details are discussed in the papers themselves.

3.1.1. Scope and functional units

The complete life cycle of each system—*Sköna Hem*'s print and tablet systems—was covered in Papers I and II, from extraction of raw materials and manufacturing to distribution, use, and waste management in the year 2010. *Sköna Hem* is a Swedish monthly magazine on interior design, with two additional special issues in 2010. Two tablet versions of the magazine were studied:

- **Emerging version**: the current (2010) version of the magazine, based on actual figures for 2010. The tablet edition of the magazine in its emerging version was not a mature product in 2010. The number of copies (i.e., downloads) was low (2212 electronic copies per year, compared with 1,307,600 print copies per year), and the reading time per copy (9 minutes) was low compared with that of the print copy (41 minutes).
- **Mature version**: To consider the tablet edition in a more mature version, we included a scenario where the number of tablet copies was increased, so that half the current number of print copies was replaced by tablet copies (i.e., in total 653,500 print copies and 653,500 tablet copies per year). The reading time was also increased, to equal the time an average reader spends on the print copy (41 minutes).

The functional unit is the definition of the benefit provided by the product system and gives a reference to which the inputs and outputs can be related. For the study presented in Papers I and II, the basic functional unit was defined as:

- One reader's use of one copy of *Sköna Hem*'s print and tablet version, respectively, in 2010.

Previous comparative studies on media products have shown that the functional unit choice is of great importance for results of environmental performance (Hischier & Reichart, 2003). Thus in Papers I and II we also calculated results using two other functional units:

- One hour of reading *Sköna Hem*'s print and tablet version, respectively, in 2010.
- One copy of *Sköna Hem*'s print and tablet version, respectively, in 2010.

3.1.2. Data collection and data sources

A comprehensive quantitative LCA is normally performed using a software tool for LCA. Such tools often include databases that can be used in the inventory analysis. In the LCA presented in Papers I and II, SimaPro 7.2.3 and the format and data categories therein were used.

Data were primarily chosen from actors in the supply chain of the product studied. For example, data from the environmental product declarations (EPDs) published by the paper production company and the Swedish postal services ("Posten") were also used. When this was not possible, data were taken from the Ecoinvent 2.2 database (Ecoinvent Centre, 2010) and modified to reflect the corrections made in the Ecoinvent 3.0 version to datasets associated with integrated circuits (both memory and logic types) and with network access devices.

3.1.3. Allocation procedures

Allocation problems occur when there are several products or functions from the same process. Environmental impacts need to be allocated between these different functions. The following is a brief description of how the allocation for each situation was applied in Papers I and II.

Allocation of content production. Environmental burdens of the content production, shared between the print and tablet edition, were allocated based on the number of copies (the impact of activities specific for the tablet edition was accounted for in this edition only). There were 0.5 full-time employee equivalents (FTEs) specifically working with the tablet version, and thus this was naturally accounted for in that product system. For the rest of the content production environmental impact, an allocation was made based on the number of copies sold; 2212 electronic copies per year and 1,307,600 print copies per year gives 0.2% of the rest of the content production environmental impact to the tablet emerging version. In total, 1.7% of the content production was allocated to the tablet emerging version. For the mature version, this share was 50%, i.e., 653,500 electronic copies per year and 653,500 print copies per year. The production of content was accounted for as total electricity use, heating, cooling, business trips, transportation by delivery firms, electronic office equipment and office paper used. These processes are described in further detail in Paper I. For all these processes, information was gathered from *Sköna Hem* for the year 2010. The data provided do not cover production of advertisements, which was excluded from the assessment.

Allocation of electronic storage and distribution. The allocation of environmental impacts for electronic storage and distribution in Paper I-II was based on the size of the data (megabytes) transferred over the network except for home networking (modem/router), the allocation of which was based on reading time of the tablet edition. This allocation approach was consistent with that used in previous studies on electronic distribution of media (Coroama & Hilty, 2014; Coroama et al., 2015b; Koomey et al., 2004; Moberg et al., 2011; Schien et al., 2013; Weber et al., 2010).

Allocation of reading the tablet magazine. The impact of production, distribution and disposal of tablet was allocated to the reading of the tablet edition, based on the use time. This is consistent with the allocation approach adopted in previous studies of electronic media (Moberg et al., 2010, 2011). The overall use time of the tablet studied was assumed to be 14 hours/week (in the reference scenario) during a 3-year lifetime. To assess the impact per reader and per copy, only 9 minutes in the emerging version (41 minutes in the mature version) of this overall use time were allocated to reading a copy of the tablet edition.

3.1.4. Impact categories

In Papers I-II, the environmental impacts were measured using the life cycle impact assessment method called ReCiPe (Goedkoop et al., 2009) at Midpoint (H) and also cumulative exergy and energy demand (Bösch et al., 2006; Frischknecht et al., 2007). ReCiPe Midpoint (H) version 1.06 includes 18 impact categories. Of these, only results from categories with sufficient underlying data for analysis are presented in Papers I-II. Table 1 shows the list of impact categories assessed in Papers I-II. Results are also presented as cumulative energy and exergy demand for both the print and tablet edition in Papers I and II.

Table 1. List of impact categories assessed in Papers I-II (* denotes categories included in the respective study)

Impact categories		Paper I	Paper II
ReCiPe midpoint indicators	Climate change	*	*
	Human toxicity	*	
	Photochemical oxidant formation	*	*
	Particulate matter formation	*	*
	Terrestrial acidification	*	*
	Freshwater eutrophication	*	*
	Marine eutrophication	*	*
	Terrestrial ecotoxicity	*	
	Freshwater ecotoxicity	*	
	Marine ecotoxicity	*	
	Metal depletion	*	*
	Fossil depletion	*	*
Energy and exergy	Cumulative Energy Demand	*	*
	Cumulative Exergy Demand	*	*

3.2. How System Dynamics is applied in Papers III-V

One of the major studies addressing the dynamic and systemic aspects of environmental effects of ICT is that commissioned in 2002 by the European Commission's Institute for Prospective Technological Studies (IPTS) to explore the current and future environmental effects of ICT employing a quantitative SD approach. The aim of that study (here called "the IPTS study") was to estimate positive and negative effects of ICT on environmental indicators with a time horizon of 20 years. The method applied was to develop future scenarios, build a model based on the SD approach, validate the model and use it to run quantitative simulations of the scenarios. The results of the IPTS were published in 2003 and 2004 in five interim reports (e.g., Hilty et al. (2004) describe the model and data used), one final report (Erdmann et al., 2004) and several articles (see Hilty et al. (2006)). Paper III revisited the assumptions and results of the IPTS study in light of the developments observed during the past decade (Figure 5). The arrows and text in red in that diagram show the activities performed in this revisiting process. The upper part of Figure 5 presents the role of scenarios A, B, and C in the original study. Paper IV in this thesis discusses the feedback mechanisms used in the IPTS study to model the rebound effects of the efficiency offered by ICT applications.

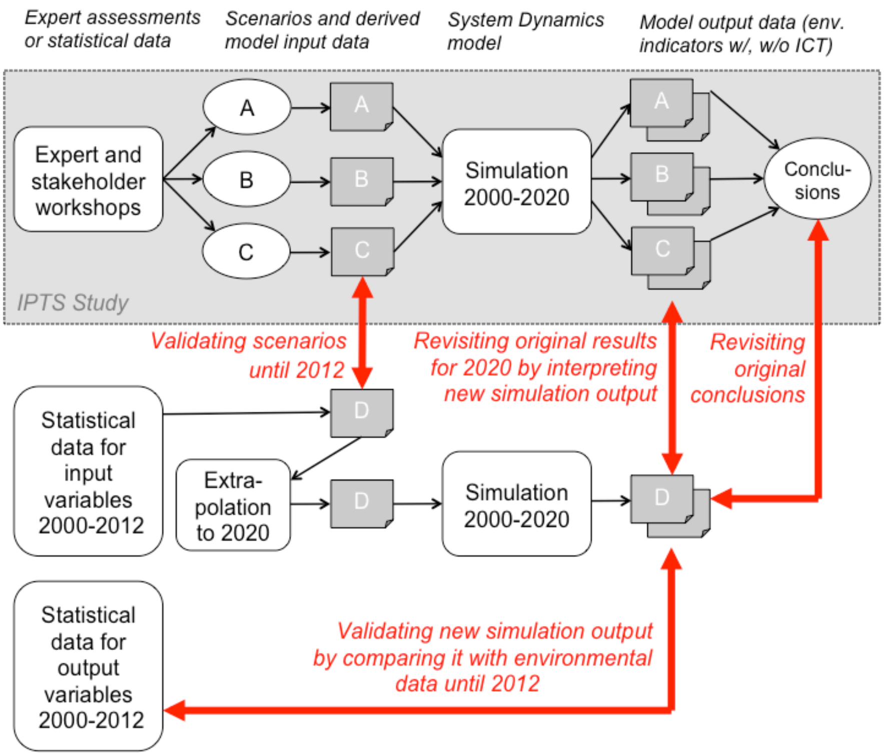

Figure 5. Phases in revisiting the IPTS study in Paper III (Diagram from Paper III).

The aim of the IPTS study was to estimate the following environmental indicators for the year 2020 and to isolate the effect of ICT on these: (1) total freight transport, (2) total passenger transport, (3) modal split (private car transport vs. public transport), (4) total energy consumption, (5) the share of electricity generation from renewable sources, (6) greenhouse gas emissions, and (7) municipal solid waste not recycled.

The idea of the IPTS model was to enable simulation experiments in which one could "switch on" and "switch off" ICT trends—such as teleworking, mobile working, virtual meetings, intelligent transport systems (ITSs), and intelligent heating—and observe how this switching affects the indicators.

Three levels of ICT effects were considered in the IPTS study: *First-order effects*: The impacts of the life cycle of ICT hardware, for example, the energy consumed by the ICT hardware of an intelligent transport system. *Second-order effects*: The impacts of the services provided by ICT applications, for example, the energy saved in transport by using an ITS. *Third-order effects* (including rebound effects): The systemic effects of ICT on the economy, for example increased demand for transport as a long-term implication of efficiency gains induced by ITS applications.

A simulation experiment makes a prediction of the form "if…then," where the "if" part is represented by the input data used to feed some of the model variables and the "then" part by the output data generated by calculating other (dependent) model variables. It is the conditional nature that makes a prediction different from a forecast, which calculates future values of all model variables based on their initial values only (Kelly et al., 2013). Strictly speaking, a forecast is a special case of a prediction. The simulation experiments in Paper III were based on scenarios of the type called "What-if" scenarios in the typology of Börjeson et al. (2006). These scenarios were developed in expert workshops and described in natural language. The simulation input data were derived from the "if" part of the scenario. This included, for example, future changes in the price of oil and other quantities considered to be external factors and thus input variables to the model. The model then simulated development under the assumptions made in the scenarios. Because the simulation experiments only differed by the input data derived from the scenarios, these data vectors were called "scenarios" in Paper III.

Figure 2 summarizes the main elements used to model these three levels in the IPTS study, showing the abstract causal structure of the SD model and main variable groups. For example, the rebound effect, i.e., the induction of demand by increasing the efficiency of a production or consumption process, as a third-order effect of ICT can be captured in feedback loops in the IPTS study (as discussed in Paper IV). The rebound effect in the IPTS study, as shown in the abstract representation of the causal structure of the SD model in Figure 2, is represented by the increase in demand for a service (e.g., passenger transport) due to a decrease in the price/time per service unit (e.g., cheaper or faster transport), which in turn is related to cost/time efficiency provided by ICT.

Paper V explored the power of systems modeling and simulation to represent nonlinearities of the complex and dynamic systems examined in Papers III and IV. That study reviews previous studies that have compared the SD and AB approaches and models, summarizing their purpose, methodology, and results, based on certain criteria for choosing between SD and AB approaches. The transformation procedure used to develop an AB model for purposes of comparison with an SD model is also explored.

4. Summary of results of Papers I-V

This chapter summarizes the results obtained in Papers I-V.

4.1. Papers I and II

Paper I presents the life cycle assessment of the tablet edition of a Swedish interior design magazine, distinguishing between the emerging version (when readers are few and reading time is short) and the mature version (assuming more readers and longer reading time). Paper II presents the life cycle assessment of a print magazine and compares the environmental impacts of the magazine's tablet edition with those of the print edition.[3]

4.1.1. LCA of the tablet edition

The results for the tablet edition (Paper I) indicated that the potential environmental impact of the tablet edition of the magazine differed considerably between its emerging and mature versions (Figures 6 and 7). In the emerging version the content production was the major reason for the impact, while in the mature version it was mainly electronic storage and distribution.

The higher contribution of content production in the emerging version was due to the tablet-specific environmental impacts of content production activities being split between so few readers. With major changes in the media sector, which may lead to lower costs for publishers related to the distribution and electronic devices replacing print on paper, it may become economically feasible to produce content for a smaller number of copies. In that case, content production may rise as a major reason for the environmental impacts of media consumed on multi-purpose and energy-efficient devices.

Previous studies on electronic media report a dominant impact of the use phase, whereas Paper I identified the importance of number of readers. The use phase (reading on tablet), which includes the manufacturing of the device and the electricity for using it, was the main contributor to environmental impacts related to the tablet magazine only when there were many readers and low overall use of the tablet device.

The results of the sensitivity analysis in Paper I for electricity mix illustrated the importance of geographical scope and the electricity mix used for processes related to the tablet magazine product system, with the Swedish electricity mix generally giving rise to a lower environmental impact than the UCTE average mix tested. Moreover, the results of the sensitivity analysis for the size of the electronic magazine in Paper I showed the environmental advantage of smaller file size.

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[3] Note that the results presented in Papers I and II, which are published in the Journal of Industrial Ecology (Achachlouei & Moberg, 2015; Achachlouei et al., 2015), are slightly different from the results presented in previous publications (Achachlouei 2013; Achachlouei et al. 2013; Hischier et al., 2014) associated with the same project on the LCA of *Sköna Hem*. These changes reflect corrections made in the original manuscripts of Paper I and II in response to comments of the anonymous reviewers of the Journal of Industrial Ecology.

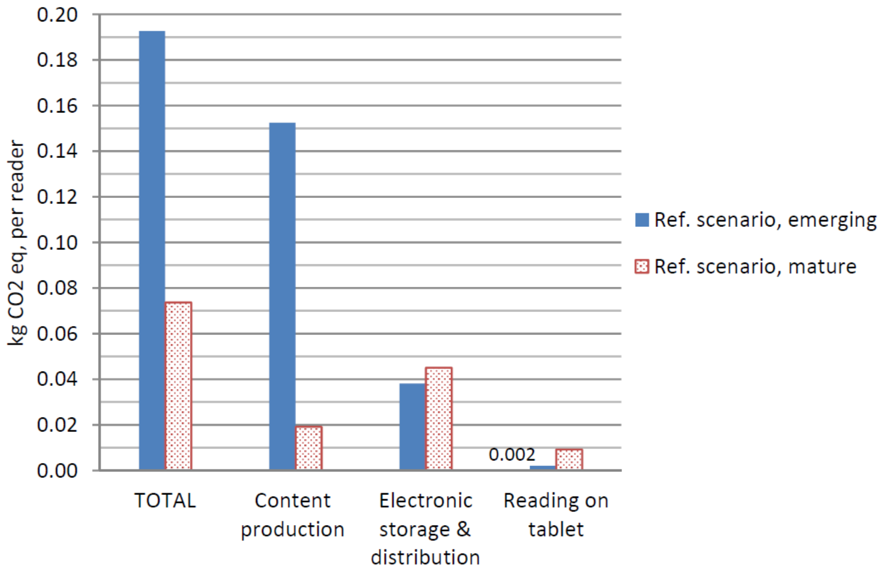


Figure 6. Climate change impact of the tablet magazine in the reference scenario (per reader of a copy) (diagram from Paper I).

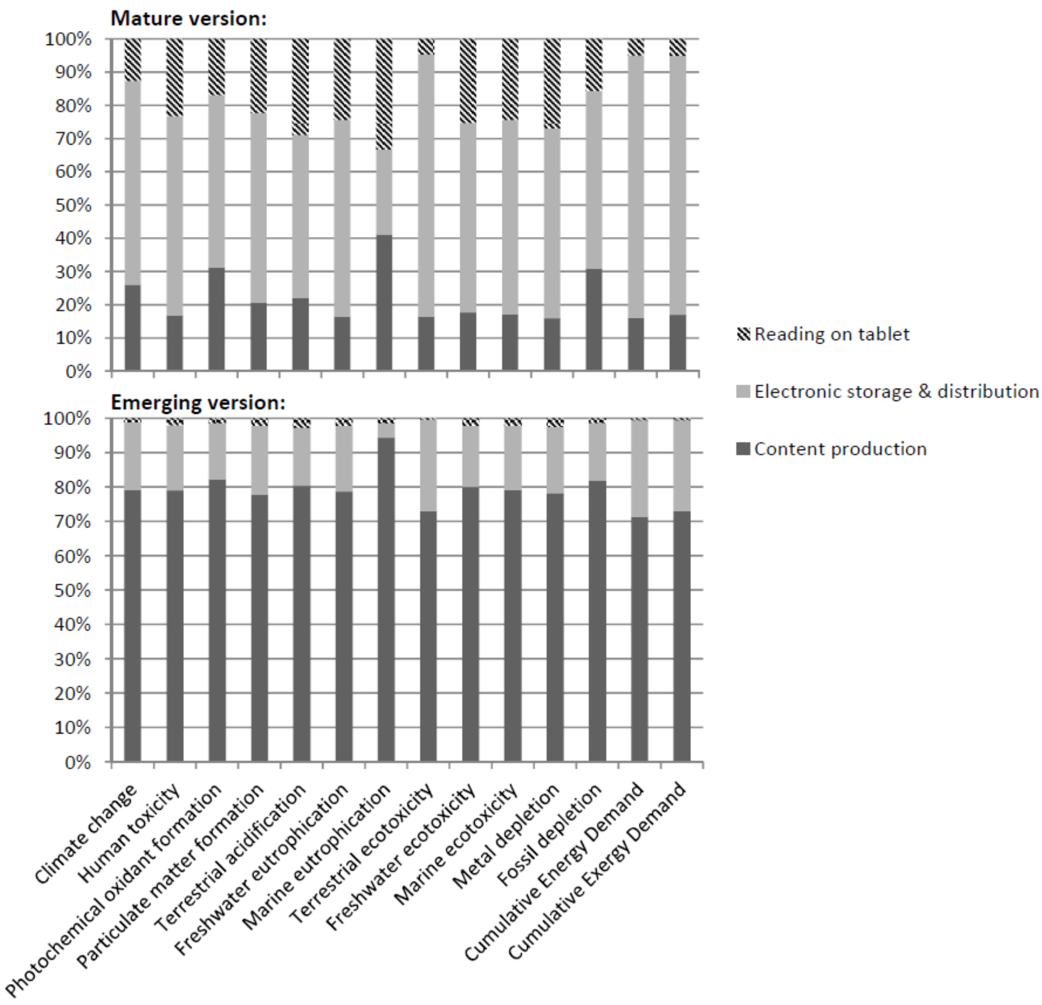


Figure 7. Environmental impact of the tablet edition magazine in the selected categories for the reference scenario (per reader of a copy): Emerging version (current 2010) and mature version (possible future) (diagram from Paper I).

4.1.2. LCA of the print edition

For the print edition, as shown in Figure 8, pulp and paper production was the main contributor to the potential environmental impacts except for metal depletion impact, for which printing was the main reason. The recycling of the waste magazine paper may considerably offset environmental impacts if newsprint production from virgin fiber can be avoided.

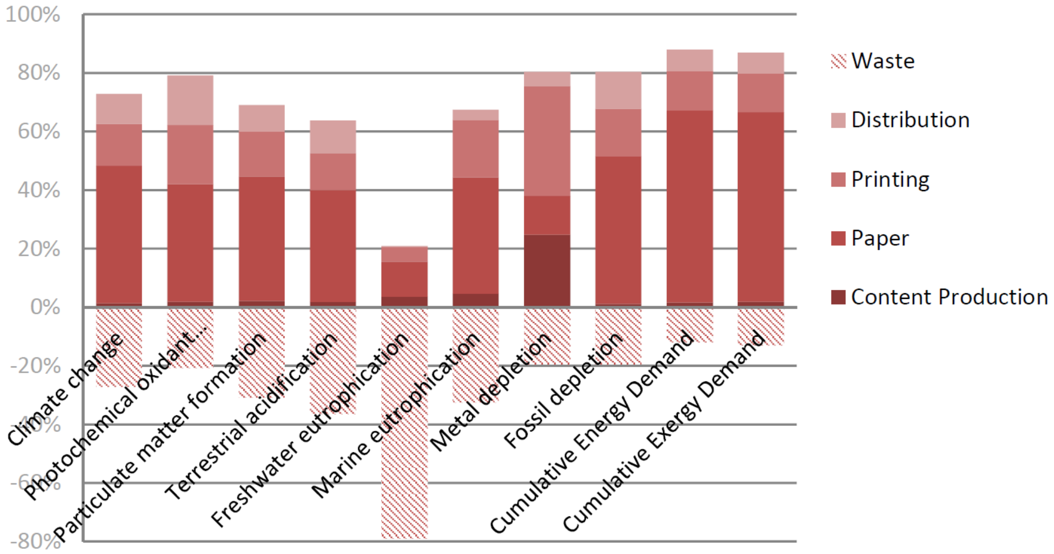


Figure 8. Relative contribution of the different life cycle phases of the print edition to the environmental impact categories studied in Paper II for the reference scenario (diagram from Paper II).

4.1.3. Comparison of tablet and print editions

When comparing the tablet and print edition of the magazine studied, the importance of the functional unit became clear (see Figure 9 for impact per reader and Figure 10 for impact per copy). Whether the tablet edition was in the emerging or the mature version also made a considerable difference.

Three different functional units were used within the overall assessment. The emerging tablet edition gave rise to more environmental impacts *per reader* than the print and mature tablet edition for most impact categories. Furthermore, it gave rise to even more environmental impacts *per reading hour*. This is a consequence of the emerging edition having fewer readers and also lower reading time per reader.

On the other hand, when the environmental impacts were related to *a copy* of the magazine, the print edition gave the highest environmental impacts in most impact categories.

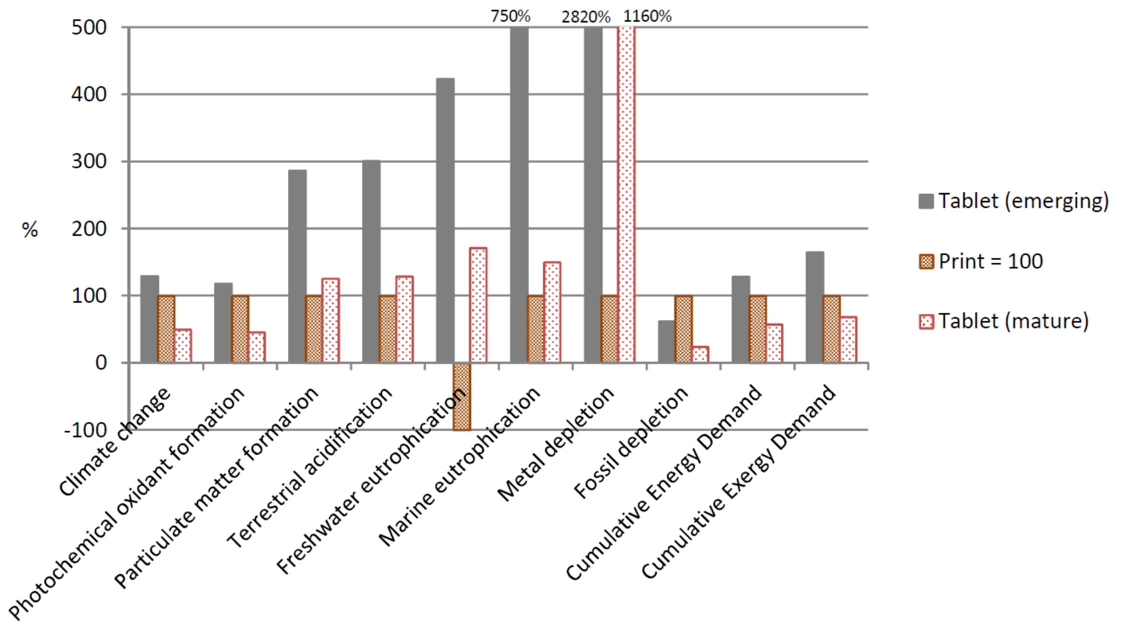


Figure 9. Comparison between print and tablet editions of the magazine in the reference scenario (impact per reader). Print reference scenario = 100 (diagram from Paper II).

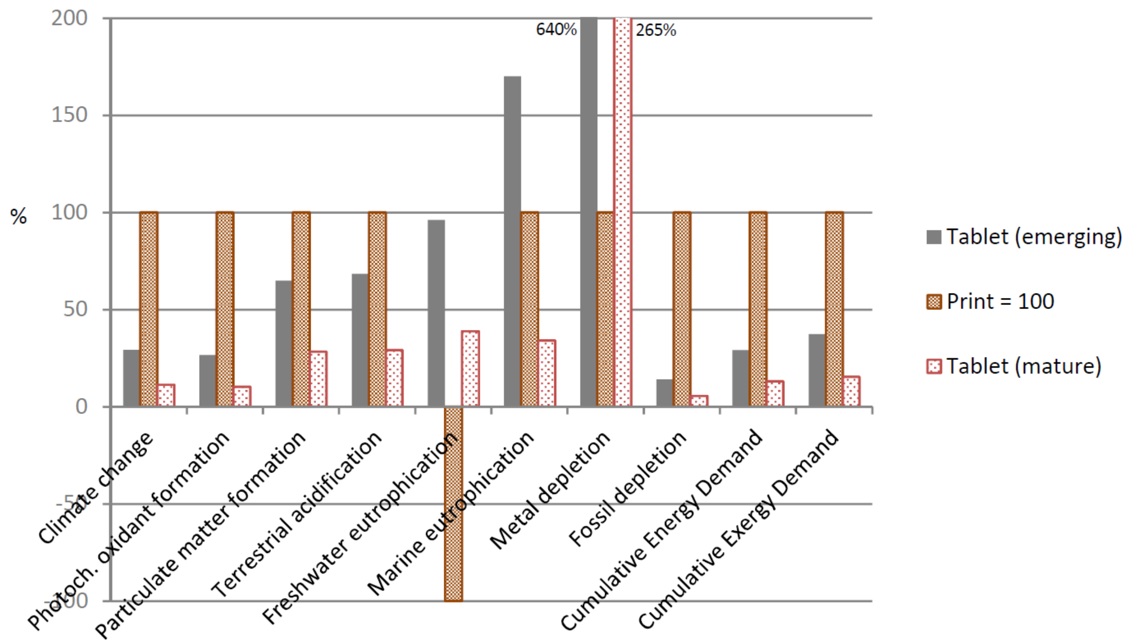


Figure 10. Comparison between print and tablet editions of the magazine when the impact is assessed per copy as the functional unit. Print = 100 (diagram from Paper II).

4.2. Paper III

Paper III addressed the following three research questions:

1. Which of the three scenarios in the IPTS study (briefly described in Table 2) comes closest to reality?
2. Are the main trends the IPTS model predicts for a realistic scenario consistent with the currently available data?
3. Can the main quantitative and qualitative results regarding the impact of ICT provided by the IPTS study be confirmed or rejected and their uncertainty reduced by the currently available data?

Table 2. Brief descriptions of the original scenarios in the IPTS study; Scenarios A, B and C. *Note*: In the IPTS study, given the fundamental difficulty in forecasting the external factors over 20 years, the project team applied a scenario approach to deal with the uncertainty. In expert and stakeholder workshops, three possible futures were developed in the form of scenarios, each representing a development that was internally consistent and plausible according to the participants' assessment. Brief descriptions of the original scenarios are repeated in this table (Hilty et al., 2004).

Scenario A "Technocracy"	This scenario was characterized by strong economic growth, leading to an increase in the workforce that was also reflected in an increase in desk workers due to the service-based nature of the economy. Strong growth also led to a significant increase in the total number of households and buildings due to increased economic activity. Collusion between government and business determining the framework for business activity is dominated by large companies, which was reflected in a decrease in the number of small and medium-sized enterprises (SMEs).
Scenario B "Government first"	This scenario was characterized by weak economic growth, which was reflected in lack of growth in the number of households, buildings and desk workers. The total labor force decreased due to stagnating economic growth and the flight of industry from Europe. The settlement pattern became more dispersed due to the development and high take-up of environmental and social applications of technology, for example ITSs, smart homes and virtual conferencing. This also led to an increase in the percentage of SMEs.
Scenario C "Stakeholder democracy"	This scenario was characterized by steady economic growth, leading to an increase in the number of households and desk workers and the total labor force. A reduction in the levels of inequality between the developed and developing worlds and the expansion of the EU to 35 Member States reduced immigration to Europe and, as a result, the expected rise in population did not materialize. The settlement pattern became more dispersed due to business investment in applications that can improve virtual conferencing and smart home technologies.

To investigate the first research question, Paper III collected empirical socio-economic data for the period 2000-2012 (see Table 1 in Paper III) and found that none of the three scenarios developed by experts in the IPTS study (to specify the external factors needed to run the model) were realistic from today's point of view. The second and third research questions in Paper III were investigated through re-running the IPTS model with more realistic input data for the first half of the simulation period, defining a new scenario, Scenario D, based on the empirical data available today.

On running the model for scenario D, Paper III found that the predictions were roughly plausible (see Figure 11 for the simulated trend for freight and passenger transport index, chosen as an example)[4], but they cannot be taken as precise predictions. The purpose of the model was not to predict the development of the environmental indicators in absolute terms, but the relative impact of ICT on these indicators.

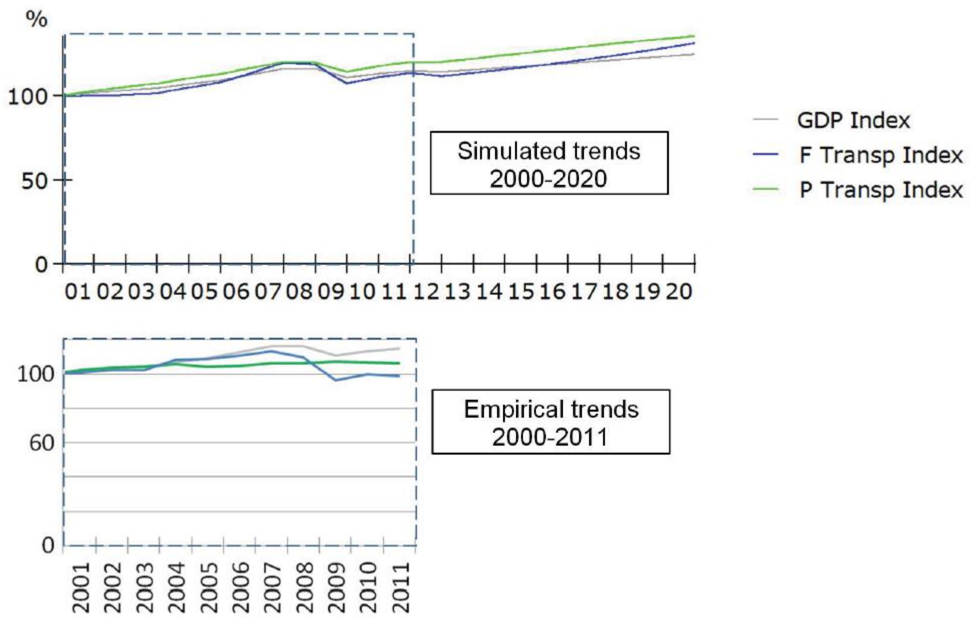


Figure 11. Comparison of simulated trends (Scenario D) with empirical trends. F Transp: Freight transport; P Transp: Passenger transport (Diagram from Paper III).

ICT impact index. The role of ICT was assessed in Paper III by comparing the values for the reference simulation run with the values from the "ICT freeze" run[5]. This comparison, referred in Paper III to as ICT impact index, was defined as:

$$\text{ICT Impact Index} = \frac{\text{the value for the reference simulation run}}{\text{the value for the corresponding ICT Freeze run}}$$

= 1 means that ICT has no influence on the environmental burden

> 1 means that ICT increases the environmental burden

< 1 means that ICT reduces the environmental burden

Table 3 presents the ICT impact index for all sub-scenarios for both the original scenarios A, B and C and the new scenario D. Discussing the meaning of the values of ICT impact index for each environmental indicator, Paper III found that

[4] See supporting material in Paper III for more simulated trends (Achachlouei & Hilty, 2014b; Achachlouei & Hilty, 2015)

[5] In Paper III, two versions or runs of the given scenario were examined: One which simulates the development of ICT as it is predicted over the simulation period (called reference run) and one which "freezes" ICT diffusion and use at the level of the year 2000 (called "ICT freeze" run). An "ICT freeze" switch was built into the model for that purpose.

the main results regarding the impact of ICT remained qualitatively the same (see Table 4); they seemed to be relatively robust implications of the causal system structure, as represented in the model. Overall, the impacts of ICT in mitigating greenhouse gas emissions and other environmental burdens for 2020 tended to be slightly stronger when the simulation was based on the empirical data now available.

Table 3. ICT impact index (the value for the reference simulation run divided by the value for the corresponding "ICT freeze" run) for the five main output variables of the model used as environmental indicators. The *worst*, *best* and *mean* sub-scenarios were created to account for the uncertainty of parameters. The *worst* sub-scenarios exploit parameter uncertainty to maximize the environmental indicators and the *best* to minimize them; the *mean* sub-scenarios are based on setting each parameter to the average of its min and max values (table from Paper III)

ICT impact index	A worst	A mean	A best	B worst	B mean	B best	C worst	C mean	C best	**D worst**	**D mean**	**D best**
Freight Transport	1.04	1.01	0.90	1.32	1.27	1.11	1.03	0.98	0.83	**0.99**	**0.95**	**0.81**
Passenger Transport	1.03	1.02	1.01	1.04	1.04	1.02	1.03	1.02	1.00	**1.03**	**1.05**	**1.04**
Energy	0.98	0.95	0.89	1.03	0.99	0.92	0.97	0.93	0.85	**0.94**	**0.90**	**0.82**
GHG	0.97	0.93	0.87	1.03	0.98	0.90	0.97	0.92	0.83	**0.81**	**0.89**	**0.79**
Materials	0.90	0.88	0.79	1.00	0.97	0.87	0.90	0.86	0.74	**0.85**	**0.83**	**0.71**

Note: A value of 1.0 means that ICT has no influence, values >1 mean that ICT causes an increase in the environmental indicator by this factor, i.e., ICT causes more environmental burden. Values <1 (shown with grey background) indicate that ICT reduces the environmental burden.

Table 4. Revisiting the main conclusions of the IPTS study (cited from Hilty et al. (2006)) by checking them against the new results produced for Paper III. (Table from Paper III)

Main conclusions of the original IPTS study	Main conclusions revisited
ICT applications supporting a product-to-service shift (virtual goods) "Although there are widely diverging opinions concerning an ICT-supported product-to-service shift and its potential energy saving and dematerialization effects until 2020, it is the high potential for change that makes this issue important. In the model, almost every output turned out to be directly or indirectly linked to the product-to-service shift variables, first of all freight transport, but also waste and the energy used by the industrial sector."	*Confirmed by new results.* ICT has a reducing influence on total material demand (dematerialization effect).
ICT applications for heating management (intelligent heating) "ICT has a high potential impact on the rational use of heating energy. Heating accounts for roughly 30% of total energy consumption and conservation measures using physical materials tend only to be applied to the small annual share of buildings that is renovated or newly built. 'Soft measures' using ICT (such as intelligent heating systems) have the advantage of being applicable in all buildings, and could therefore have a significant effect."	*Confirmed by new results.* ICT has a reducing effect on energy consumption in the domestic and tertiary sector, which is dominated by heating.

Table 4. (continued)

ICT applications for passenger transport efficiency "All ICT applications that make passenger transport more time efficient (such as ITSs) will create a rebound effect leading to more traffic and possibly more energy consumption. Induced passenger transport demand has severe environmental consequences in energy use and greenhouse gas emissions, although ICT contributes to lowering the energy and GHG intensity of passenger transport."	*Confirmed by new results.* ICT has a stimulating influence on total passenger transport by making it more cost- and time-efficient (rebound effect).
ICT applications for mobile work "Mobile work enabled or supported by pervasive computing and other new forms of ICT application can have a significant effect on passenger transport, because it increases the share of time spent in traffic that people can use productively. This can create more transport demand, while stimulating public transport more than private car transport. The effects of ICT on personal time management and time utilization are probably the most underestimated indirect impacts of ICT on the environment, with great potential in either direction."	*Confirmed by new results.* Time utilization effects of mobile ICT create an advantage for public transport compared with private car transport.
ICT applications for freight transport efficiency "All ICT applications that make freight transport more cost efficient (i.e., cheaper) will immediately create more freight transport and more energy consumption. There is no evidence for assuming anything other than a strong price rebound effect here. By making transport more cost efficient, ICT creates freight transport demand, with severe environmental effects, unless measures are taken to limit demand of transport."	*Not confirmed by new results.* ICT is now slightly inhibiting growth of freight transport. This ICT effect is mainly due to its dematerialization effect, which is stronger than in the original study.

4.3. Paper IV

Paper IV investigated the feedback loops (closed causal chains) used in representing the rebound effects in the SD model described in Paper III (called Model 1: the submodel of the IPTS study on passenger transport demand and modal split) in comparison with another study (Peeters, 2010) (called Model 2 in Paper IV) that modeled the dynamics of how pollution-saving technologies positively or negatively affect the demand for tourist transport and greenhouse gas emissions. Two kinds of direct rebound effects were considered in Models 1 and 2: direct economic rebound induced by increased cost efficiency and time rebound induced by increased travel speed.

The results of the comparative analysis in Paper IV showed that both Model 1 and Model 2 employed causal loop diagrams to explore the dynamics of transport volume (in passenger-kilometers, pkm). Better understanding and estimation of the demand for transport volume are important, because energy demand and greenhouse gas emissions are associated with transport volume.

Model 1 represents direct economic rebound effects via cost efficiency loop and resource scarcity loop (Figure 12). Time rebound effects in Model 1 are modeled via a travel time budget mechanism and mode shift loop (Figure 12), which work with time (not money, as is the case for cost efficiency loop and resource scarcity loop); a central variable is the speed of transport of each mode.

Model 2 contains three reinforcing feedback loops, including travel time loop, cost loop and mode shift loop, and one balancing loop, i.e., max speed loop (see Figure 13).

The main comparative results obtained in Paper IV were as follows:

- Both Models 1 and 2 represent the same types of rebound effects in passenger transport: Cost efficiency loop, resource scarcity loop and travel time budget mechanism.
- Both Models 1 and 2 are multi-modal transport models, also considering the dynamic change of modal split.
- Both models employ the concept of economic elasticity of demand with regard to price. However, Model 1 addresses this in a more explicit way in terms of presenting elasticity parameters for different transport modes.
- Both Model 1 and Model 2 use the constant travel time budget assumption in a similar way to show the dynamics of speed versus demand; higher speed implies using the constant time budget to cover more distance.
- Both models show that efficiency cannot necessarily reduce total emissions if the transport volume increases because of reinforcing feedback loops described above—both time rebound and direct economic rebound.
- Both models include similar external variables, such as population and economic growth, as drivers of transport demand.
- The efficiency loop modeled in Model 2 includes investment in efficiency enhancing technology. However, investments are not explicitly represented in Model 1.

It was concluded in Paper IV that the contribution of the systems thinking and modeling approach to rebound analysis originates from: its holistic approach; its capability to build upon existing empirical knowledge about what rebound is and how it functions; its capability to represent various policy options and intervention scenarios; and its support for integration of rigorous simulation tools with high-level diagramming tools that can be used easily by a variety of stakeholders in a collaborative modeling environment. Future work may employ systems thinking and modeling in designing policy instruments, addressing both efficiency and rebound effects in a holistic perspective.

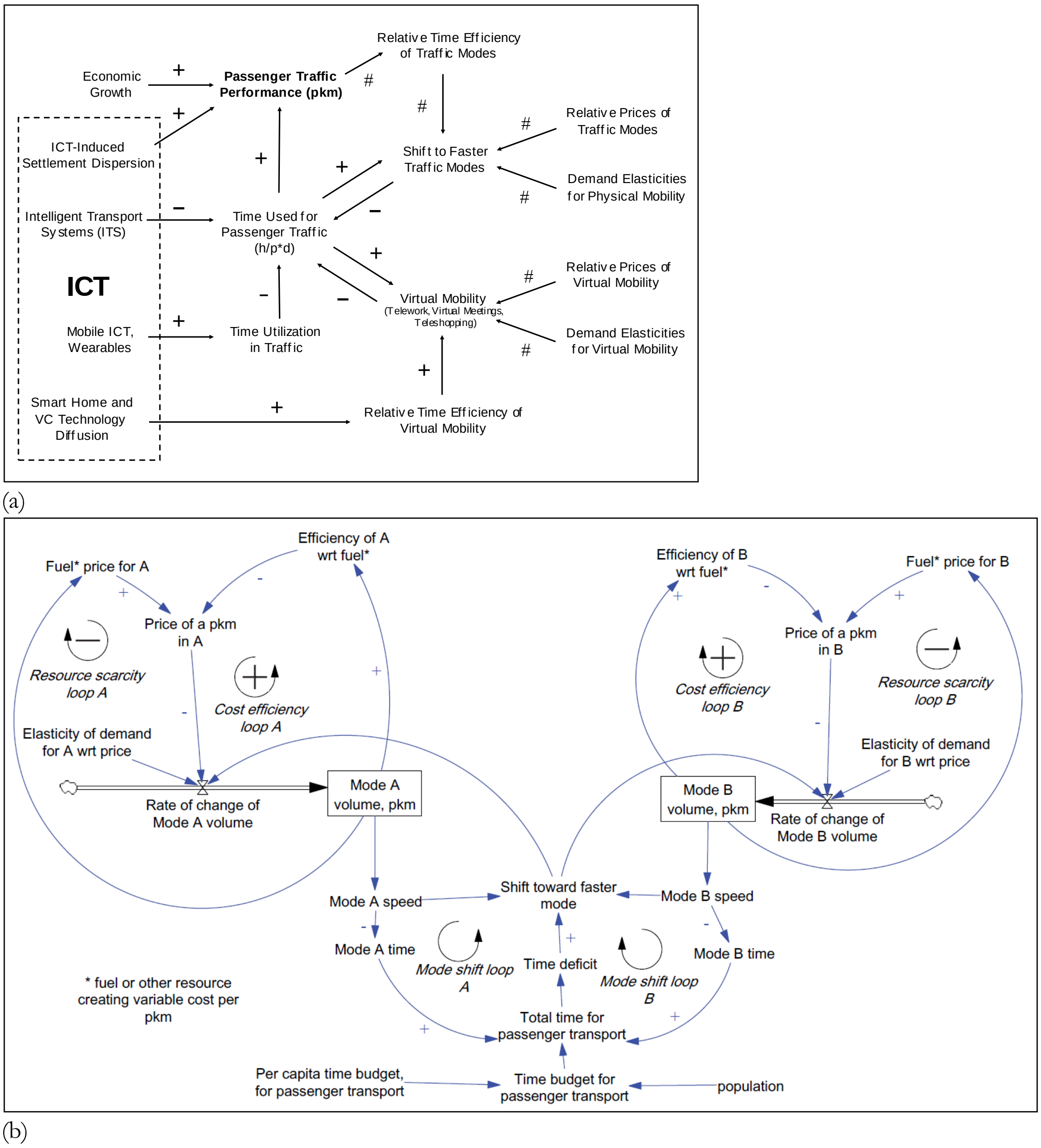
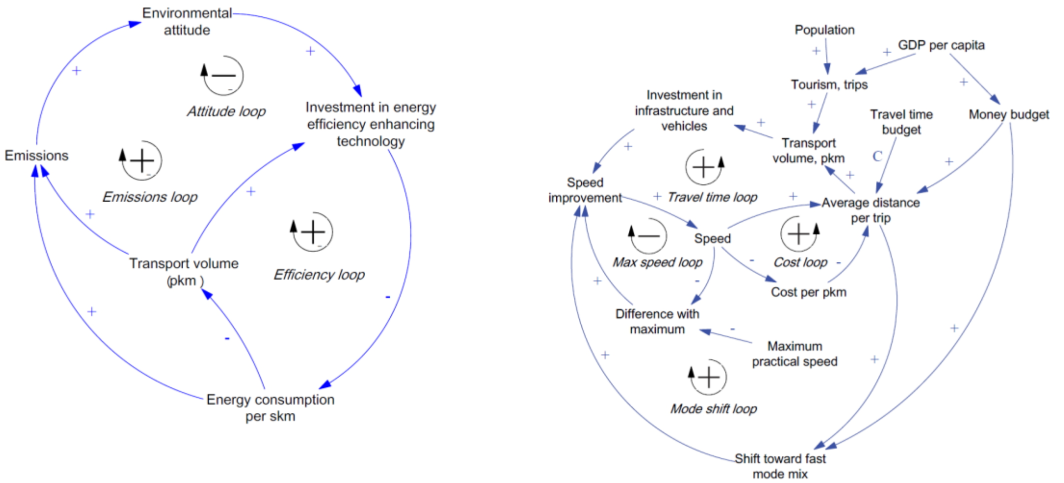


Figure 12. Causal loop diagram for Model 1: (a) A more abstract diagram of the development of passenger transport performance, taken from the IPTS interim report (Hilty et al., 2004): "ICT has second-order effects when applied to passenger traffic (all applications subsumed under Intelligent Transport Systems) and third-order effects in the long term via settlement dispersion, time use in traffic, smart home and videoconferencing technology. The '#' sign is used where the multidimensional variables are involved, leading to complex causal relationships." (b) A less abstract diagram focusing on main feedback loops.



(a) (b)

Figure 13. Causal loop diagram for Model 2 in Paper IV: (a) Pollution-saving loops. (b) Basic forces in transport systems. *Note*: Time delay is indicated by the double strikethrough lines in the arrows) (diagrams taken from Paper IV and Peeters (2010).

4.4. Paper V

After examining the effects of ICT using a SD approach in Paper III, in order to further investigate the capability of complex systems modeling in sustainability assessments, Paper V reviewed studies comparing the SD and AB approaches and models. The aim was to gain a better understanding of the differences between the two modeling approaches in general; to clarify when these approaches are appropriate and what must be taken into account when utilizing them; to clarify the comparison method employed by different studies; to determine how to design simulation studies to compare models based on these two approaches and what procedures can be used to build corresponding SD and AB models in such comparative studies; and to highlight the advantages of employing comparative studies in the field of sustainability assessment.

For this purpose, Paper V reviewed previous studies comparing SD and AB modeling to analyze their aim, methodology, and results of comparison. Two groups of comparative studies were reviewed: those comparing the approaches in general without conducting experiments (Group A); and those building corresponding SD and AB models and comparing the results from simulation experiments (Group B).

Aim of comparison of SD-AB modeling in the studies reviewed

Regarding the aim of comparison, Paper V found that the studies reviewed mentioned various reasons for comparing SD and AB approaches and models. The main purpose of comparing SD and AB approaches and models (in Groups A and B) was to provide insights about when to choose the SD approach and when it is appropriate to use AB modeling. In addition to this aim, comparative studies with model comparison (Group B) sought to enhance knowledge and inform modeling research communities in certain domains, for example immunology—where differential equation modeling (quantitative SD) is considered an established modeling approach—about the capabilities of the relatively new approach, i.e., AB modeling. Thus comparative studies, including experimentation and model comparison (Group B), employ the two different approaches to build multiple models in order to address the same problem and to better understand the system under study with less uncertainty.

Methodology used for SD-AB comparison in the studies reviewed

Regarding the methodology employed by the studies for comparison of SD-AB modeling (Group B), Paper V highlighted the main stages explicitly or implicitly followed in the studies comparing SD and AB models given the same modeling problem. In order to build corresponding models for comparison purposes, some studies start from a given AB model and create at least one equivalent SD model, and some start from the SD model and build an AB model. For example, Wilson (1998) and Rahmandad & Sterman (2008) start from an AB model, but Macal (2010) and Figueredo et al. (2013) follow a SD-to-AB modeling path.

Comparison of SD-AB results in the studies reviewed

In terms of comparison of results, Paper V presents the results of the studies reviewed in Group A with regard to the criteria defined in those studies for choosing an appropriate method when addressing a given modeling problem. Table 5 summarizes the results of comparisons in the studies reviewed with simulation experiments (Group B).

Table 5. Summary of results of comparisons in the studies reviewed (Group B) in Paper V

Study	Result of SD-AB comparison
Wilson (1998)	- The study compares an AB model of predator-prey system with a series of SD models, including a deterministic and stochastic SD model. - The deterministic SD leads to qualitatively different behaviors than the AB model. - The study finds good agreement between AB results and the stochastic SD results under various dispersal scenarios.
Rahmandad & Sterman (2008)	- The SD and mean AB dynamics differ for several metrics relevant to public health, including diffusion speed, peak load on health services infrastructure, and total disease burden. - The response of the models to policies can also differ even when their base case behavior is similar. - In some conditions, however, these differences in means are small compared with the variation caused by stochastic events, parameter uncertainty and model boundaries.
Macal (2010)	- Probabilistic elements in the SD model were identified, isolated and translated into probabilities that are used explicitly in the AB model. For the SIR epidemic model, the two probabilities were related to agent contact and to agent transmission of infection. - The equivalence of the model results is not exact in terms of numerical accuracy for the reasons noted. - The study shows that the AB model is able to provide information beyond what the SD model provides due to the explicit stochastic nature of the AB model.
Figueredo et al. (2013)	- It is possible to obtain equivalent AB models from a given SD model (i.e., implementing the same mechanisms). - However, the simulation output of both types of models might differ depending on the attributes of the system to be modeled. - In some cases, additional insight can be obtained using AB modeling. - Overall, the authors confirm that AB modeling is a useful addition to the toolset of immunologists, as it has extra features that allow for simulations with characteristics that are closer to the biological phenomena.
Parunak et al. (1998)	- The SD model shows the same periodicities as the AB model. - The SD model does not show many of the effects observed in the AB and in real supply networks, including the memory effect of backlogged orders, transition effects or the amplification of order variation.

Lessons learned from comparison methodology—a transformation procedure

The studies reviewed (with simulation experimentation; Group B) built equivalent models to perform the comparison. Based on lessons learned from the methodology of model-based comparison in those studies, Paper V highlighted the transformation procedure used to build an AB model given a SD model using examples from the studies reviewed. The reason Paper V highlighted this procedure, as a subordinate step in the studies reviewed, is that: (i) this procedure is one of the aspects of the studies reviewed and thus fitted the scope of the review; (ii) it is insightful to formulate this procedure to better understand differences between the SD and AB modeling approaches; (iii) the procedure provides user guidance for future comparative studies; and (iv) even when comparison of the two models is not intended, given the availability of either a SD or AB model it is useful to be able to reuse knowledge embedded in one type of model through following such a procedure to build a new model of the other type.

The main steps of the transformation procedure, which was demonstrated through two examples in Paper V, are as follows:

1. Identify populations and their respective states in the SD model:

Step 1.1: Identify populations in the SD model.

Step 1.2: For each population identified in Step 1.1, list the states associated with the population. Stock variables, which are differentiated over time, guide the analyst towards these states.

2. Define agents and agent states:

Step 2.1: For each population identified in Step 1.1, define an agent (class) *a,* to represent the members of the population.

Step 2.2: For each population state S in the SD model (identified in Step 1.2), define a state variable s for the respective agent a (associated with the population) in such a way that $s_a = S$.

3. Identify the flows between stocks in the SD model and define transition rules between agent states (see Figure 14):

Step 3.1: Identify the flows between stocks in the SD model

Note: the flows between stocks at the population level in the SD model are equal to the sum of the underlying probabilistic transition rates for each population member.

Step 3.2: Define transition rules between agent states of the agent associated with the population.

4. Add heterogeneity in individual attributes:

Step 4.1: Identify individual attributes (agent parameters) based on the parameters used in formulating transition rules defined in Step 3.2.

Step 4.2: Add heterogeneity in individual attributes.

Note: The studies reviewed, when designing the comparative experiments, chose various approaches to represent heterogeneity in AB models.

5. Add network structure (heterogeneity) for agent interactions

Note: The contact network (or relationship network, or social network) is a feature of modeling that is specific to AB modeling, and we could not find an explicit equivalent part in the SD model.

Step 5.1 Add a network for the interaction of agents.

6. Add spatial heterogeneity and mobility

Step 6.1 Add spatial heterogeneity and mobility to the AB model.

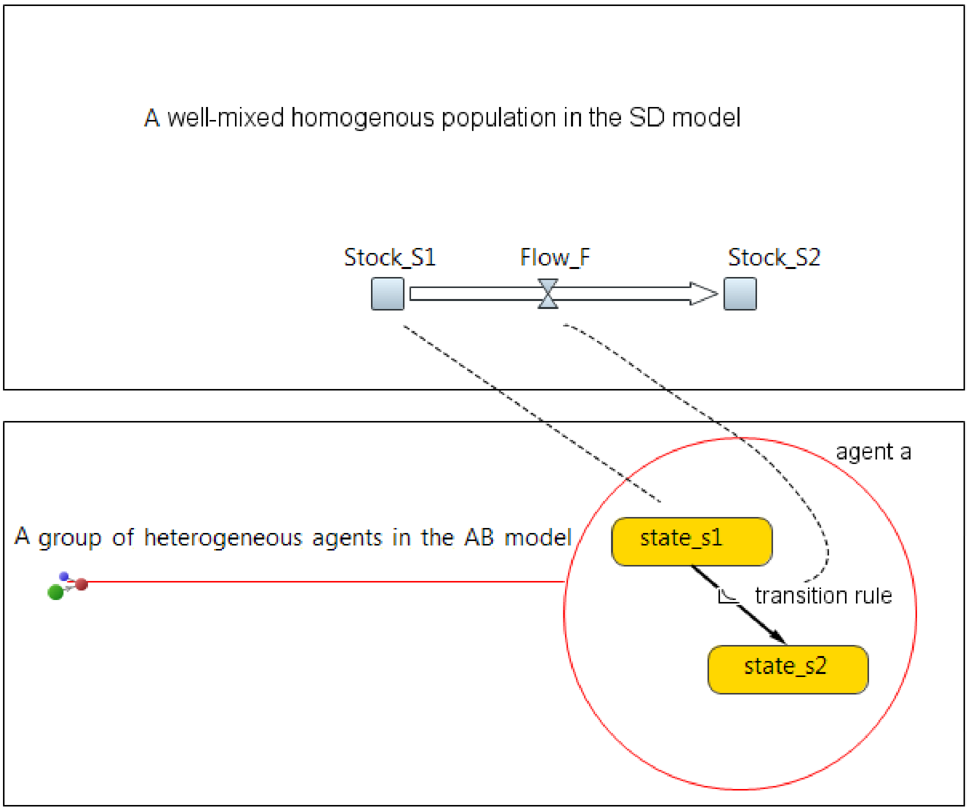


Figure 14. Visual demonstration of mapping the elements of an SD model onto the relevant elements in the equivalent AB model. The dashed line depicts the mapping of the stock variable and flow function in the SD model onto the agent state and transition rule, respectively, in the AB model. The homogeneous value of a stock variable in the SD model at any time during the simulation corresponds to the average value of the respective agent state in the population of heterogeneous agents. The red circle represents only one agent ("instance") among the group of agents, corresponding to the population in the SD model.

When comparing models in simulation experiments, the studies reviewed in Paper V used the same parameters for both the AB and SD models. Some studies, starting from a given AB model, built a corresponding SD model through averaging over population of agents, and others used a SD model as the starting point and built an equivalent AB model through adding heterogeneity in individual attributes and interaction networks among agents. In addition to reviewing the methods employed by the comparative studies, Paper V also highlighted a transformation procedure for disaggregating an SD compartmental model into a more heterogeneous AB model.

Further comparisons of SD/AB models in the field of sustainability assessment would provide an opportunity to better understand the dynamics of the social, economic, and ecological systems through providing complementary macro and micro perspectives and managing the model uncertainty rooted in the modeling approaches. Micro-level AB models would provide a different analysis instrument than the macro-level SD models for analysis of the behavior of the base case system and also under various policy interventions. Comparison of analyses conducted using macro-level SD models and micro-level AB models would increase the quality of model-based sustainability assessment and the associated scenario analysis and policy simulations.

5. Discussion

5.1. Three types of ICT effects studied in this thesis

The results of Papers I-V can be viewed in light of the three-level effects of ICT on environment presented in a framework in Section 2.1 (Figure 1), which shows positive and negative impacts of ICT. Table 6 summarizes these effects as studied in this thesis.

First-order or direct effects of ICT—including environmental impacts of production, use, and disposal of ICT—can be assessed using the LCA method. In this thesis, the LCA method was used to explicitly assess environmental impacts of life cycle activities of the tablet device and the infrastructure for electronic storage and distribution in Papers I-II. Direct effects of ICT in this framework (Hilty & Aebischer, 2015) only include negative effects—not positive effects by definition. However, positive direct effects such as raising social awareness on environmental sustainability via reading magazines can be included. (This issue is not covered in this thesis.)

Second-order or enabling effects of ICT, with the focus on applications, were taken into account in the thesis. LCA is also well suited for assessments comparing ICT applications with conventional alternatives. Paper II addressed this through applying LCA to compare an ICT application (the tablet edition of the magazine) with its conventional alternative (the print edition of the magazine). Using the LCA approach Paper II revealed that a tablet edition in an emerging state, with few readers and low reading time, resulted in higher potential environmental impacts per reader (except for fossil depletion) than the print edition. Assuming more readers and longer reading time for a mature tablet edition, the impacts per reader were lower than for the print edition in half the impact categories assessed. The print edition resulted in lower impacts in the metal depletion and freshwater eutrophication categories in all analyses performed. In the comparative approach in Paper II, the LCA method implicitly included partial substitution (dematerialization) and/or complete substitution (virtualization) of the print edition of the magazine, thus avoiding or reducing environmental impacts associated with the print edition. Moreover, the System Dynamics model in Paper III represented the potential of ICT applications for substitution (of products and processes) and/or optimization. Moreover, parameter-based scenario analysis helped to model the speed at which this potential would be realized (see the abstract causal structure in Figure 2).

Third-order or systemic effects (including rebound effects) of ICT with the focus on behavioral and structural changes were partly taken into account in the thesis through complex and dynamic systems modeling and simulation techniques discussed in Papers III, IV, and V. Paper III employed feedback loops derived from efficiency potentials, economic elasticity of demand and travel time budget to model rebound effects associated with cost- and time-efficiency provided by ICT. Paper IV highlighted and discussed these mechanisms. Paper III, through simulation modeling of the systemic and rebound effects of ICT, concluded that ICT can induce additional demand via rebound effects, particularly in the field of passenger transport, given the socio-economic conditions of 15 European countries. As for a recommendation for future work, while the rebound effects of energy efficiency in transportation and buildings have been widely studied, rebound effects of ICT, particularly the time rebound, have not been investigated adequately for the ICT applications. To better understand various aspects of behavioral and structural effects of ICT, there is a need to employ mixed methods including both quantitative and qualitative methods addressing economic modeling questions and socially constructed challenges. Future work may employ systems thinking and dynamic modeling in designing policy instruments, addressing both efficiency and rebound effects in a holistic perspective.

Table 6. Three types of ICT effects studied in the thesis—Papers I-V (based on Hilty & Aebischer, 2015)

	ICT as part of the problem (negative effects)	**ICT as part of the solution (positive effects)**
1. Direct effects (focus on technology)	LCA explicitly assessed environmental impacts of life cycle activities of the tablet device and the infrastructure for electronic storage and distribution (Papers I-II)	n/a by definition
2. Enabling effects (focus on application)	Not addressed in the thesis	- Comparative LCA in Paper II implicitly included partial substitution (dematerialization) and/or complete substitution (virtualization) of the print edition of the magazine, thus avoiding or reducing environmental impacts associated with the print edition. - The System Dynamics model in Paper III represented the substitution and efficiency potential of ICT in various economic activities.
3. Systemic effects (focus on structural and behavioral changes)	The System Dynamics model in Paper III and Paper IV (and potentially the agent-based model in Paper V) addressed rebound effects of ICT	Not explicitly addressed in the thesis (But some positive systemic changes included in the SD model in Paper III, e.g., possibilities to work when going by public transport, can be related to these effects.)

5.2. Relationship between LCA and systems modeling and simulation

This subsection discusses the relationship between LCA and systems modeling and simulation, in particular SD and AB modeling. The relationship between LCA and systems modeling can be considered in the context of environmental systems analysis (ESA) tools[6]. Although not considered an ESA tool, SD and AB modeling can be used to model and formally describe a social-environmental system, which can then be assessed using the ESA tools. In this sense, the relationship between LCA and systems modeling is that they can be used consecutively: first SD and/or AB

[6] Examples of ESA tools are as follows (Finnveden & Moberg, 2005): Cost-Benefit Analysis (CBA); Ecological Footprint (EF); Environmental Impact Assessment (EIA); Environmental Management System (EMS); Energy Analysis; Input-Output Analysis (IOA); Life-Cycle Assessment (LCA); Life-Cycle Costing (LCC); Material Flow Accounting (MFA); Material Intensity Per Unit Service (MIPS); Strategic Environmental Assessment (SEA); System of Economic and Environmental Accounts (SEEA); Substance Flow Analysis (SFA); Total Material Requirement (TMR).

modeling, to describe the dynamics of the complex system, and then the ESA tools to assess the system. Finnveden and Moberg (2005) characterize ESA tools, e.g., LCA, with regard to aspects such as whether the tools are procedural or analytical[7], what types of impacts are included, what the object of the study is and whether the studies are descriptive (i.e., attributional or accounting studies) or change-orientated (i.e., consequential or effect-orientated studies).

Descriptive or change-orientated? Finnveden and Moberg (2005) characterize LCA as an analytical tool that can be used both as a descriptive (accounting) tool and a change-orientated tool. However, SD and AB modeling are only change-orientated tools (obviously this is their defining characteristic): The cause-effect chains, feedback loops, and rate equations in SD and behavioral rules (and utility functions) of agents in AB modeling are the main modeling constructs representing the change orientation in these dynamic approaches. Systems thinking and modeling approaches can be combined with change-oriented (or consequential) LCA to help better describe effects of change and then to better investigate the future environmental consequences of technological choices today (Sandén and Karlström, 2007).

Types of impacts? Systems modeling methods (SD and AB here) can be used together with LCA focusing on assessment of the environmental impacts and resources used throughout a product's life, but not the economic aspects (Finnveden & Moberg, 2005). However, SD and AB modeling have the potential to be used together with other ESA tools (such as IOA and LCC) to assess not only the resources used and environmental impacts, but also economic aspects.

Study object? The object of study is another aspect of characterizing ESA tools. A variety of objects can be studied. The object can be a substance, a function, a product, an organization, a nation, a region, a project, a policy, a program, or a plan. This aspect can guide the analyst to a certain choice of ESA tools. LCA is traditionally used for the assessment of products and services (for instance, in Papers I-II, LCA was used to assess a magazine product system). Systems modeling and simulation approaches in principle can be used together with ESA tools as evaluation techniques for different types of objects, augmenting such tools in providing a dynamic perspective. For example, in Paper III, SD was used at a regional level to explore the future impact of ICT on a number of environmental indicators in 15 European countries. However, SD and AB modeling, when integrated with a certain ESA tool, can be applied to the object being studied by that tool. For instance, in Stasinopoulos et al. (2012), when SD is integrated with LCA, they are applied to a

[7] Procedural tools "focus on the procedures and the connections to its societal and decision context, whereas analytical tools focus on technical aspects of the analysis." "Analytical tools can be used within the framework of procedural tools" (Finnveden & Moberg, 2005). Note that the term "analytical tool" in this context should not be confused with "analytical models" (in the context of mathematical and computational modeling) which refers to mathematical models that have a closed form solution, i.e. the solution to the equations used to describe changes in a system can be expressed as an analytic function. "Analytical models" can be compared with "numerical models," which are mathematical models that use some sort of numerical time-stepping procedure to determine model behavior over time. The solution is represented by a table and/or graph. Source: http://serc.carleton.edu/introgeo/mathstatmodels/numerical.html (Accessed: April 22, 2015)

product/fleet (which is the study object here). However, when SD is combined with MFA, in dynamic material flow analysis, aiming to model metal stocks and flows (e.g., Müller et al., 2014), the object of study is a substance. As for AB modeling, different types of objects can be studied. In Köhler et al. (2009), AB modeling (using SD to represent complex agents) is applied at a societal or national level (UK). Davis et al. (2009) integrate AB modeling with an iterated, accounting-type LCA to assess a bioelectricity infrastructure system (as the object being studied) while it evolves.

System boundary in LCA and the role of qualitative SD. Systems thinking (qualitative SD) methods can be used in LCA to provide a broader view when we decide on what to include in the system boundary of the LCA study. Laurenti et al. (2014), employing a group-based qualitative SD "to identify potential sources of environmental impacts outside the scope of LCA studies," note a number of limitations associated with LCA: Optimizations suggested by LCA are not well-suited for addressing the interrelations between the products and the infrastructure system (e.g., how consumers use the products considering the available infrastructure) and the consumption response to income change, product improvements and policy resistance. Laurenti et al. (2014) then argue "products are not part of an isolated life cycle (i.e., cradle to grave). On the contrary, there are different levels of connections among the natural and technical environments, consumers, and other products or services." For example, noting that "consumption patterns may affect resource availability in a regional or global perspective," Laurenti et al. (2014) suggest that such important variables and links can be taken into account through supporting LCAs with two techniques associated with qualitative SD, i.e., group model building and causal loop diagrams to delimitate "appropriated system boundaries for LCA" and identify variables or domains to be included in sensitivity and scenario analysis.

5.3. Data collection prioritization: A philosophy of science perspective

In this subsection, I will reflect on my experience with data collection for the LCA study presented in the thesis. In the inventory phase of the LCA study in Papers I and II, data on inputs and outputs of each life cycle activity were gathered: inputs of material and energy, outputs of emissions (to water, air and ground), and waste.

In an ideal scenario, an analyst could expect to collect all inventory data associated with life cycle activities of the product system under study. However, in the real world, given the uneven maturity of environmental information systems and also accounting approaches used in industry, it is difficult, sometimes impossible, for the analyst to gather all data. Furthermore, since every LCA study is a project with specific goals and certain resource constraints (e.g., time and budget), the analyst must consider the data collection process within these constraints.

During the LCA study in Papers I and II, the necessity, importance and cost of collecting the necessary data were often substantial. It was reasonable, of course, not to gather data which were outside the study's scope. However, there were moments when the sought-after data were inside the defined scope, but due to considerations associated with study goals or project constraints, it was necessary to prioritize the data collection tasks. In these instances, I usually followed published assessments or other expert advice in deciding whether to gather or omit certain data.

The next questions are: What are the scientific foundations of expert judgments in such data collection prioritization? How can we prioritize which data to collect in order to minimize the cost of the assessment and maximize its reliability?

As Alan Chalmers (2003) notes: "At least since the writings of Karl Popper and Thomas Kuhn made their impact on the philosophy of science it has become commonplace to regard observation and experiment in science to be theory-dependent in some significant respect."

Theory dependence in natural science means that our observations "start out from our conceptions about what types of empirical observations are most suitable for finding out the regularities in nature. These conceptions, in their turn, are not 'purely theoretical', but are based on previous empirical observations" (Hansson, 2007, p. 33).

Interpreting this definition in the context of the research method used in the present thesis (i.e., LCA), we can maintain that theory dependence in LCA means that our data collection process (in the inventory phase) starts from our conceptions about what types of empirical evidence are most suitable for analyzing environmental impacts of the product system under study (to achieve the study goals).

For instance, consider the following example of data collection on the cover paper of the magazine in Paper II:

> Two types of paper are used in the print magazine, one for inset and another for cover. The inset consists of the paper NovaPress 75 g/m^2 (gloss) and the cover is Tom&Otto 200 g/m^2 (gloss), both produced in Finland.
> Data from the environmental product declarations (EPDs) were used (Stora Enso, 2011). The EPDs include figures on the following environmental parameters: emissions to water (COD, AOX, N and P) and air (CO_2, SO_2 and NO_x), electricity consumption and solid waste landfilled. The figures cover the production of pulp and paper.
> The pulp used for the cover paper is produced in Brazil. The forestry data were not available, but it is transported by ship to Finland (Partanen, 2011). The transportation was modeled using the Ecoinvent dataset "Transport, transoceanic freight ship/OCE" (Spielmann et al., 2007).
> Data on the forestry used to provide pulp for cover paper are lacking. Because of confidentiality, the production mill did not provide more details. However, since the cover paper represents only 5.5% of the magazine, the details of its forestry were overlooked.

For the cover paper, inventory data were collected on the production of pulp and paper and on distribution; however, the data on forestry were missing (the data were not provided by the company due to confidentiality). As reasoned above, since the share of the cover paper is only 5.5% of the total paper used in the magazine (and the forestry data for the inset paper, which has the 94.5% share, had been collected), the details of the forestry for the cover paper were obscured.

This can be seen as an example of a theory-dependent observation which assumes a similarity between the level of impact of forestry associated with cover paper and that of forestry associated with inset paper. This assumption could be questioned, since forestry in Finland and in Brazil could have very different impacts in terms of e.g., land use and associated impacts on carbon flows and biodiversity.

In order to quantify the extent to which a scientific inquiry is theory-dependent, one can employ e.g., Bayesian networks[8] (Neapolitan, 2004) for assessing environmental impacts. These networks can be combined with a diagnosis algorithm for prioritizing which data to collect in order to minimize the cost of the assessment, without harming its scientific objectivity. This is a topic for future research. Relating this question to uncertainty analysis approaches in LCA, one could benefit from Bayesian statistics-based approaches developed in the field of LCA (Lo et al., 2005).

5.4. Limitations and need for future research

5.4.1. Data gaps and uncertainties in LCA of ICT

In the LCA studies in Papers I-II, there were major data gaps concerning the toxicological impact categories for the pulp and paper manufacturing if specific data were to be used, while relevant information on printing supply material was also limited. Thus, these impact categories were not assessed for the print version. Using generic data for the electronic components of the tablet provides more comprehensive datasets, but these are not specific to the actual product type studied and thus uncertain (see Moberg et al. (2014) for a discussion relating to this issue in their study on mobile phones). Moreover, these generic data are quite old. Such data gaps are also reported in other LCA studies of ICT and electronic media.

In the case studies, some data were not available at all or were not of the desired quality, so assumptions had to be made or data gaps introduced, e.g., in the case of server electricity use, which was calculated based on assumptions. In contrast, the data on e.g., printing house operations are in many cases well documented. This indicates the differences in assessment of old and new media products and the differences in company awareness and experiences from previous requests and assessments.

In the case studies performed in Papers I and II, the use of specific and national data for the printed newspaper system meant that it was not possible to cover as many impact categories for the printed media solutions as for the electronic. The comparison was made in only seven impact categories, considered to be relatively well covered for both versions. Even though this is broader than the carbon footprint assessments commonly presented, it clearly illustrates that there are data gaps that still need to be filled. Improved data are needed for both product systems studied in Papers I and II for further studies and more comprehensive assessments.

Inherent uncertainties are related to user practices, as these vary between different users and over time. In the reference scenarios in Papers I and II, the aim was to describe an average user and to highlight emerging and mature states over time. The information and assumptions used in the study were tested in sensitivity analyses as presented in Papers I and II. However, future work on assessment of the environmental impact of electronic media would benefit from collecting data on heterogeneous consumers and how they change their behavior of using various print

[8] Bayesian networks are often employed for probabilistic inference. Bayesian networks are composed of three components: nodes, representing system variables; values (probabilities) associated with nodes; and arcs between the nodes, representing causal relationships between these nodes.

and electronic media over time. Employing complex and dynamic systems modeling, social networks and common frameworks can be utilized for simulating consumer behavior, e.g., the Consumat model (Jager et al., 2000; for an application of the framework e.g., see Xu et al., 2009), which accounts for cognitive processes (repetition, deliberation, imitation and social comparison) in order to explore the complexity and dynamics of the media market and its environmental costs.

5.4.2. Need for statistical data on ICT effects on sustainability

The IPTS study employed many socio-economic and ICT-related parameters, where initial values and annual rates of change for a certain parameter were important. In the revisiting effort presented in Paper III, empirical data were collected from statistical sources such as EuroStat, which is the statistical office of the European Union. EuroStat regularly maintains statistics on the Information Society, tracking the usage of ICT in enterprises, households and individuals in European societies. However, many ICT-relevant parameters used in the study (e.g., average teleworking hours and average lifetime of ICT devices in the EU) were not covered by EuroStat, and it was difficult to find empirical data on the trends of such parameters. Future work could provide detailed data requirements for systematic and comprehensive tracking of development and usage of ICT. The European Commission regulation[9], on which Eurostat's provision of data on the Information Society is based, covers a variety of ICT-related subjects, including "use of ICT and its impact on the environment (Green ICT)"[10]. Since Eurostat's 2014 edition of its *Methodological Manual for Statistics on the Information Society*[11], which provides methodological support for the aforementioned regulation, does not address variables and statistical tools on the Green ICT subject, there is future potential to develop methods and data for the impact of ICT on the environment within the framework of Eurostat. This type of information could also be a valuable source for LCA studies of ICT products and services.

5.4.3. Need for ICT sustainability indicators

The studies performed so far on sustainability assessment of ICT can inform global measures of sustainable development and the information society. The current ICT indicators, for example the ITU[12]'s annual reports on "*Measuring the Information Society*" (ITU 2013), are limited only to technical development of ICT. Further research is needed to conceptualize and implement the ICT sustainability index in relation with existing index systems, such as the United Nations' Sustainable Development Goals and the ITU reports.

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[9] Regulation (EC) No 808/2004 of the European Parliament and of the Council of 21 April 2004 Concerning Community Statistics on the Information Society (OJ L143, 30.04.2004, p. 49). The latest amendment of (EC) No 808/2004 is Regulation (EC) No 1006/2009 of the European Parliament and of the Council of 16 September 2009 (OJ L286, 31.10.2009, p. 31)

[10] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:286:0031:0035:EN:PDF (Accessed: April 22, 2015)

[11] https://circabc.europa.eu/faces/jsp/extension/wai/navigation/container.jsp (Accessed: April 22, 2015)

[12] ITU: International Telecommunication Union, the United Nations specialized agency in telecommunications

5.4.4. Integrating LCA and systems modeling approaches

In this thesis, LCA and systems modeling were employed independently to explore the direct and indirect effects of ICT on environmental sustainability. However, it is possible to use both LCA and systems modeling techniques in an integrated framework. Such integrated frameworks are useful considering the potential of systems modeling approaches to capture the dynamics of changes over time and space in sustainability assessments.

For example, Stasinopoulos et al. (2012) use SD in a consequential, fleet-based LCI model that compares the life-cycle energy consumption of car body-in-whites (BIWs) in Australia made from steel and aluminum. SD supports the modeling of two dynamic processes: the flow of BIWs into and out of the fleet, and the recycling of aluminum from end-of-life BIWs back into new BIW production. Stasinopoulos et al. (2012) use this SD-based LCI model to compute both product-based and fleet-based estimates, concluding that a SD approach is a "potentially useful way to account for temporal effects in LCI computations."

In another example, Halog and Manik (2011) develop an integrated systems modeling framework using system dynamics (and/or AB modeling) for life cycle sustainability assessment, integrating dynamic system modeling into life cycle thinking methods (such as LCA, LCC, and social LCA) and stakeholder analysis supported by multi-criteria decision analysis.

Future work on integrating LCA and systems modeling approaches could provide more case studies addressing the following questions: How can LCA and systems modeling approaches be better integrated to inform important sustainability questions? How can data be exchanged efficiently between LCA and systems modeling software tools?

5.5. Other methods for sustainability assessment of ICT

To explore environmental sustainability effects of ICT, this thesis focused on LCA and also two systems modeling approaches, i.e., SD and AB modeling. There are other methods for environmental sustainability assessment which can be employed in the assessment of ICT effects—Methods such as material flow analysis (MFA), risk assessment, life cycle costing (LCC), system of economic and environmental accounting (SEEA), input-output analysis (IOA), environmental impact assessment (EIA), and environmental auditing.

Some of these methods, e.g., MFA, have been already used to address questions about ICT effects on environmental sustainability (e.g., Steubing et al., 2010). Future work reviewing the literature on various methods used for sustainability assessment of ICT would be valuable. A further step would provide a research agenda for new studies needed to address the unanswered questions regarding the direct and indirect impacts of ICT. For example, a combination of SD modeling (addressed in Paper III) and economic modeling would be useful for quantifying various rebound effects of ICT.

6. Conclusions

The aim of this thesis was to explore methods for modeling and assessing the environmental effects of information and communication technology using life cycle assessment and also complex systems modeling techniques including System Dynamics and agent-based modeling. The main findings of Papers I-V are used below to draw conclusions about how the three levels of ICT effects on sustainability were addressed using the methods employed in those studies. The main objectives introduced in Section 1.2 of this thesis were addressed as follows:

(1) Assess environmental impacts of production and consumption of an ICT application from a life cycle perspective and compare its environmental impacts with those of a conventional product system

Papers I and II employed the LCA approach to focus on the tablet edition of a Swedish magazine, where environmental impacts of the tablet edition were assessed and also compared with those of the print magazine. Paper I showed that the relative impacts of the tablet magazine would decrease considerably with high numbers of readers, their efficient use of the tablet (i.e., for many purposes over a long life of the device) and a smaller magazine file. Paper II showed that the use of different functional units to compare the print and tablet editions of the magazine resulted in different relative environmental impacts. Paper II also showed that overall number of readers for the tablet edition, number of readers per copy for the print edition, file size, and degree of use of the tablet device proved crucial for the tablet/print comparison results. The limitations in the inventory data in Papers I and II were associated with old generic data for manufacturing of electronic devices and components; uncertainties in waste treatment processes of the tablet device; the manufacturing inventory related to data transmission; and the IP core network being limited to GHG emissions. Further studies should focus on environmental impact categories that are currently often overlooked, such as toxicity impacts and land use, and on up-to-date, more specific and comprehensive data. The LCA of the ICT application studied (the tablet edition of a magazine) identified that, while previous studies on electronic media have reported a dominant impact of the use phase, in the present study this was not the case and the number of readers played an important role. With few readers, content production (in the emerging version) was the major cause of the environmental impacts. With a higher number of readers (in the mature version), electronic storage and distribution was the major contributor to environmental impact. The use phase, i.e., reading the electronic magazine on the tablet (including the impact of manufacturing of the device and the electricity for using it), was the main contributor to environmental impacts related to the tablet magazine studied only when there were many readers and low overall use of the tablet device.

(2) Explore the dynamic future impact of ICT on environmental sustainability, including direct, indirect and rebound effects

In an assessment different from product-level analyses in LCAs, Paper III revisited a System Dynamics simulation study made in 2002 on the future impacts of ICT in 15 European countries in the period 2000-2020. On finding that none of the three scenarios of that study were realistic in light of new empirical data from 2000-2012, in Paper III a new scenario with more realistic input data for the first half of the simulation period was formulated. Simulation of the new scenario showed that the main results regarding the impact of ICT remained qualitatively the same:

- ICT has a reducing influence on total material demand (dematerialization effect);
- ICT has reducing effect on energy consumption in the domestic and tertiary sector, which is dominated by heating;
- ICT has a stimulating influence on total passenger transport by making it more cost- and time-efficient (rebound effect);
- Time utilization effects of mobile ICT create an advantage for public transport compared with private car transport;
- ICT is now slightly inhibiting growth of freight transport. This ICT effect is mainly due to its dematerialization effect, which is stronger than in the original study.

(3) Investigate the feedback loops used to represent the dynamics of direct rebound effects induced by cost and time efficiency

Paper IV highlighted and compared the feedback mechanisms used to model the direct rebound effects of ICT efficiency in passenger transport submodel (Model 1) in Paper III by comparing such mechanisms with those of another study in tourism passenger transport (Model 2). It was concluded that both Models 1 and 2 represent the same types of rebound effects in passenger transport: Cost efficiency loop, resource scarcity loop and travel time budget mechanism; both Models 1 and 2 are multi-modal transport models, also considering the dynamic change of modal split. Paper IV also concluded that the contribution of systems thinking and System Dynamics modeling to rebound analysis originates from its holistic approach, its capability to build upon our existing empirical knowledge about what rebound is and how it functions; its capability to represent various policy options and intervention scenarios; and its support for integration of rigorous simulation tools with high-level diagramming tools that can easily be used by a variety of stakeholders in a collaborative modeling environment.

(4) Gain a better understanding of the strengths and weaknesses of two systems modeling techniques, System Dynamics and agent-based modeling, in addressing dynamically complex phenomena such as the effects of ICT on sustainability

Paper V reviewed existing studies comparing the SD and AB approaches and models to better understand their aim, methodology and findings. It was concluded that both SD and AB approaches are capable of representing temporal aspects of dynamic systems, but AB approaches are more appropriate for modeling spatially explicit complex systems. AB modeling is also a better approach for modeling heterogeneity in individual attributes and in the network of interactions among population elements; however, this means that AB modeling requires the collection of more data at the level of individuals, which in turn leads to a slower modeling process, higher computational costs and more difficult calibration in AB modeling compared with the

SD approach. Paper V also formulated a procedure for building an AB model equivalent to a given SD model and demonstrated the procedure, using examples from the literature, and outlined the way in which the SD model in Paper III can be used to build an AB model to examine the dynamics of direct rebound effects of mobile ICT on passenger transport from a micro perspective.

In conclusion, first-order or direct environmental effects of ICT production, use, and disposal can be assessed employing an LCA method. This method can also be used to assess second-order or enabling effects by comparing ICT applications with conventional alternatives. However, the assessment of enabling effects can benefit from systems modeling methods, which are able to formally describe the drivers of change, as well as the dynamics of complex social, technical, and environmental systems associated with ICT applications. Such systems methods can also be used to model third-order or rebound effects of efficiency improvements by ICT. Given the methods explored in this thesis, a fruitful direction for future research would be the development of integrated methods to calculate all types of effects for a given ICT application, including the direct impact, enabling potential and rebound effects at various levels of households, organizations, economic sectors, countries, regions, and the world.

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