Environmental-Oriented Information Systems Design – The Concept of Life Cycle Impact Modelling and its Application to Cloud Computing

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Abstract: Information technology is increasingly perceived not only as a driver of economic value creation, but also as a critical factor in the context of environmental sustainability. However, it is uncertain how the adoption of a new information technology within a specific organizational context can be evaluated from an environmental perspective. Consequently, there is a great need for methods relating the organizational use of IT with environmental assessments of different information system design alternatives. This work uses an outward-looking, problem solving and interdisciplinary research approach to address this problem. It aims to evaluate the environmental impact associated with the use of information technology within an organizational context, proposing an approach to compare different design alternatives for the implementation of an information system. Thus, existing information modelling approaches are extended by (life cycle) impact modelling; a concept that is grounded in the widely considered Life Cycle Assessment (LCA) approach. The methodological foundation for this work is therefore constructivist and design science oriented.

1 Introduction

Information technology (IT) is increasingly perceived not only as a driver of economic value creation, but also as a critical factor in the context of environmental sustainability. Accounting for approximately 2 percent of the global greenhouse gas emissions, IT is part of the problem; however, by addressing the other 98 percent with IT-enabled business transformations, IT can also be a possible part of the solution [GW08]. Today, the potential of IT to reduce environmental impact seems to be extensively covered in the literature and is qualitatively affirmed for a wide range of applications [Br12, Br13, Me10, SRB13, Wa12, WBC10]. However, quantitative, outward-looking and problem solving research approaches to address the environmental outcome of a new information technology's roll out is still underrepresented [Br13, YT07]. It is uncertain how the adoption of a new information technology within a specific organizational context can be evaluated from an environmental perspective. Consequently, there is a great need for methods relating the organizational use of IT with environmental assessments of different information system design alternatives. This leads us to the following research question:

How can different information system design alternatives be compared from an environmental perspective?

This work uses an outward-looking, problem solving and interdisciplinary research approach to address this question [Br13]. It aims to evaluate the environmental impact associated with the use of information technology within an organizational context, proposing an approach to compare different design alternatives for the implementation of an information system. Thus, existing information modelling approaches [BB06, BSS09, FL04, Fr99] are extended by (life cycle) impact modelling; a concept that is grounded in the widely considered Life Cycle Assessment (LCA) approach. The methodological foundation for this work is therefore constructivist and design science oriented [He04, MS95].

A topical and still emerging example of new technological alternatives is cloud computing. Cloud computing provides the possibility to transform organizational processes by enabling a "ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources" [NI11]. Using cloud computing in business practices, as a way to reduce environmental impact, was discussed since about 5 years now [Be09, Ca13, CS13, Ga11, KMT12, Le12, WTM14]. The positive environmental effects result from improved load balancing or energetic scale effects within large-scale datacentres in particular. However, as for the application of IT in general, the question remains if the adoption of cloud computing is environmentally beneficial in specific organizational cases from the cloud users' perspective. Therefore, we will use the example of cloud migration to demonstrate the functionality of life cycle impact modelling.

Our work is structured as follows: In section 2, we review the terminology and scope of research as well as related works in the field of environmental-oriented information systems design involving cloud computing. In section 3 we introduce the concept of impact modelling. Section 4 covers the evaluation of the concept using cloud computing as an application example. Concluding remarks including implications and limitations as well as an outlook on future work is provided in section 5.

2 Research Foundation

Interdisciplinary research at the intersection of information systems, environmental and business science reveals several inconsistencies in denotation as well as terminology.

Environmental impact models and assessments show high sensitivity to inconsistent system boundary definitions often leading to incorrect conclusions and decisions [Su04]. Therefore, we will pay particular attention to the distinction between terminology and system definitions (Figure 1).

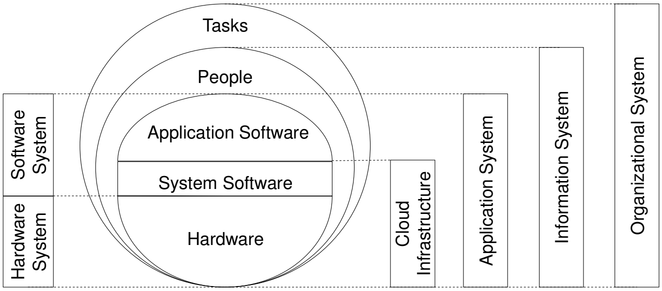

Figure 1 Systems Overview [BSS09, NI11, Te99, YBS08]

Organizational systems characterize the interaction of human, information and technology within an organization in order to fulfil certain tasks [BSS09]. Within this organizational system, *information systems* (IS) are used to fulfil the task to store, communicate and compute information [HL11]. IS involve human, information and technology, they thus constitute socio-technical systems [Te99]. The technological/IT part of the information system or *application system*, is composed of a non-physical *software system* (application and system software) and a physical *hardware system* [Te99]. The application system level is the technological level on which different technological alternatives can be compared.

A topical and recently discussed concept for an alternative implementation of application systems is cloud computing. From the perspective of IS design, cloud computing offers the opportunity to outsource parts of the application system, i.e. to reduce the amount of own physical hardware [Ak11, Le10, Nu11]. By applying one of the provided service models, the user gains access to the cloud infrastructure which is controlled and managed by the cloud provider. The application software is still located at the user, whereas the system software and hardware is located at the provider and applied via a permanent network access [NI11, YBS08]. The concept of cloud computing has thereby a significant impact on the design of information systems. Its importance for IS research is reflected by the broad interest in cloud computing at recent leading IS conferences (ICIS, AMCIS and ECIS). The relevance of cloud computing within the context of environmental sustainability is evaluated conducting a literature search to identify related work.

The literature search was conducted using a web based literature search [Br09]. The goal was to identify recent research outcomes as well as the application of cloud computing for environmental sustainability. The search was conducted querying the literature databases EBSCOhost, Sciencedirect and ISIwebofknowlege and Emerald with the search terms *sustainability*, *green* and *environment* combined with *cloud computing*. The statements within this chapter refer to the most representative and recent articles in this research area. Research on the positive environmental effects of cloud computing commonly are found using the term "green cloud computing" [QM13]. Two major strategies for reducing environmental effects can be identified:

The majority of publications associate positive environmental effects of cloud computing with a higher energy efficiency of the datacentres, caused by highly integrated computer systems and networks, improved load balancing, energetic scale effects within large-scale datacentres, virtualization as well as energy and thermal aware cloud resource allocation [Be09, CS13]. [WTM14] estimate that the replacement of organizational on-side datacentres by cloud datacentres in this context leads to greenhouse gas reductions between 31-51% depending on the size of the replaced infrastructures. Moreover, the adjustments within cloud datacentres are estimated to result in a 25 %decrease in energy consumption by improved scheduling policies [Ga11] and an increase from 33 % to 74,8 % by large scale datacentre clustering [MNV12].

The second strategy to reduce environmental impact involves transferring computing capacities towards renewable energy sources [Le12]. Using simple migration techniques, around 30 % of the non-renewable energy consumption of US cloud infrastructure can be replaced by renewable energy, such as solar or wind power [Ma13]. [Ga14] performed a case study to estimate the reduction of greenhouse gas emissions by transferring energy-intensive computational work towards datacentres with renewable energy supplies. The case study suggests that up to 30 % CO_2 emissions caused by cloud datacentres may be saved by implementing environmental oriented routing strategies.

An attempt to consider environmental metrics, energy consumption models and cost models for the design of datacentre architectures from the provider perspective has been proposed on a case based level by [Ca13]. [Ca13] provide formal energy consumption models for cloud computing from the provider perspective. A formal CO_2 aware model was offered by [KMT12]. However, despite general progress in the field of green cloud computing, recent publications reveal that positive environmental effects are being not perceived by the potential cloud users; respondents "largely neglect ecological gains in particular" [GK13]. A consumer orientation in the field of green cloud computing has not yet taken place. [CWW13] underline the importance of an environmental aware modelling approach from the perspective of cloud computing consumers. This approach, however, does not exist so far. We contribute to this highly relevant research gap by introducing an approach for integrating environmental assessment into IS design.

3 Introducing the Life Cycle Impact Modelling Approach

3.1 Overview

LCA is used to counteract assess environmental effects within the earlier stages of the supply chain [Gu02, ISO06]. Traditionally, these effects do not occur within the scope of the system design. As an example, the environmental impact of an electrical car is not completely described by its electricity consumption but also by the environmental efficiency of its energy source, e.g. a coal-fired plant or a wind turbine. Assigning this idea to the design of information systems led us to the development of a life cycle impact modelling approach for environmental-oriented information systems design.

The basic idea of the life cycle impact modelling is to help decision makers select the most environmental sustainable design alternative (represented by a To-Be-Model) for a current information system (represented by an As-Is-Model) considering not only internal factors like electricity consumption but also external factors like primary energy consumptions. Therefore, life cycle impact modelling constitutes a synthesis of process models (i.e. potentials models) [BSS09] and LCA models (i.e. inventory models) [ISO06]. Figure 2 provides an overview of the involved models as well as the numbered relations between them: (1) Initially, design alternatives for a current process (represented by an As-Is-Model) are specified using service oriented factual models. (2) & (3) Flow models (inventory models) are developed to represent physical flows associated with the design alternatives. (4) Environmental-impact models are derived from inventory models and provide a comprehensive overview of the environmental impact of the design alternatives. (5) Factual models can be further modified according to the environmental-impact model and inventory model or (6) a beneficial alternative is selected as a To-Be-Model for implementation.

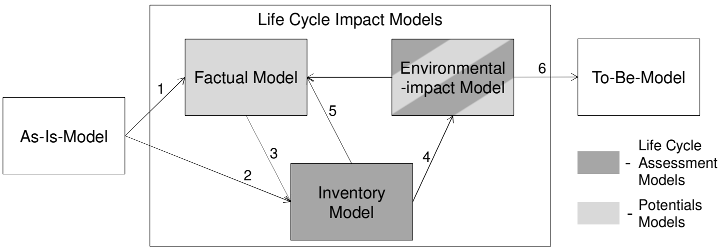

Figure 2 Life Cycle Impact Modelling Overview [ISO06][BSS09]

Proceeding from an As-Is-Model to the final implementation of the To-Be-Model involves knowledge of information modeling and LCA. Due to the type of this publication, we will restrict ourselves to the introduction of concepts that are directly relevant for the development of factual, inventory and environmental-impact models. For a deeper understanding of LCA and potentials modelling the relevant literature should be considered.

3.2 Potentials Models

Potentials models are used for the representation of different design alternatives [TB09]. According to [TB09] as well as [BSS09], potential design alternatives have to be investigated from two perspectives in order to provide a comprehensive overview of their financial and organizational consequences. Investigation should include: 1) a factual service oriented representation of the design alternatives depicting the configuration of activities, services and infrastructures using one or more factual models and 2) a value-based representation of the design alternatives depicting its economic consequences expressed by key figures within one or more value-based models.

The combination of both perspectives is required to consider the economic and business activity related consequences of a design decision. To create a factual representation, life cycle impact modelling adopts approaches advocated by [TB09] as well as [BSS09]. As the authors suggest, process modeling languages, e.g. EPC, Petri nets and UML-Diagrams, as well as the construction principles, i.e. explicit or implicit models, for the factual representation of design alternatives can be used in this regard.

A value-based representation of life cycle impact modelling focuses on environmental sustainability instead of economic sustainability. In order to avoid confusion, the environmental value-based representation of design alternatives will be called an *environmental impact model*. The environmental impact model depicts the ecological consequences of realizing the design alternative expressed by key figures. Whereas a value-based modeling considers process controlling methods, environmental-impact modeling considers LCA methods [Fi09, Gu02, ISO06] to evaluate the processes. Key figures to express the environmental impact of the design alternatives can be found among the various environmental impact categories such as [Gu02]: greenhouse gas emissions/climate change, primary energy consumptions, depletion of abiotic resources, depletion of biotic resources, stratospheric ozone depletion, impacts of land use/land competition, human toxicity, eco toxicity, photo-oxidant formation, acidification, eutrophication, impacts of ionizing radiation, odor, dust, noise, waste heat, casualties and desiccation. To derive these key figures, LCA methods involve a third perspective for investigating potential design alternatives.

3.3 Life Cycle Assessment

Life cycle assessment (LCA) is a method of compilation and evaluation of the potential environmental impacts of product systems “from raw material extraction, through energy and material production and manufacturing, to use and end of life treatment and final disposal” [ISO06]. A product in LCA can be any good or service categorized as software, hardware, service, processed material, activity performed, delivery of an intangible product or creation of ambience, performing one or more defined functions [ISO06]. Thus, from the perspective of LCA information systems, application systems, software systems and hardware systems can be interpreted as products because they offer a defined capacity to store, communicate and compute information [HL11]. Creation, use and disposal of the product involves a system of processes and physical flows called *product system* [ISO06]. In the case of information systems, the product systems involves all processes for hardware manufacturing, use and disposal, but also processes for creating electricity, creating and maintaining software, extracting and transporting raw materials that are used to create hardware components and transporting workers to their workplace. When conducting a LCA for IT/IS solutions, the complete product system needs to be represented by an inventory model, i.e. a flow diagram, consisting of energy, material and informational flows [Gu02, ST14]. Within life cycle inventory modelling, inventory models constitute a third perspective for investigating potential design alternatives (c.f. Figure 2). To ensure operability of the environmental impact modelling approach and due to the high complexity of product systems, software tools for inventory modeling as well as inventory databases containing predefined inventory models for standard products (e.g. road transportation, power generation or semiconductor manufacturing) need to be applied. Recently, two types of LCA have been distinguished – attributional and consequential [Fi09]. Attributional LCA describes the related environmentally relevant physical flows based on the currents status-quo of a product system. Typically average data for existing processes is applied [NHD11]. Therefore, attributional LCA takes a more reactionary perspective, making it less suitable for the use in IS design. Consequential LCA provides an anticipatory view on environmentally relevant flows that changes in response to possible design decisions [Fi09]. It typically involves data from marginal technologies and processes [NHD11]. Thus, a consequential LCA better supports the life cycle inventory modelling of IS design alternatives.

4 Application to Cloud Computing and Evaluation

The quality of the life cycle impact modelling approach is evaluated using the fictional case of a medium-sized newspaper publishing company. Applying fictional cases for the evaluation of design artifacts are well-accepted within the literature [BSS09, Fi12, MGR12, ST13]. Following [Te09], we will use the fictional case to evaluate our approach from three perspectives: 1) The technical quality is evaluated to prove that our approach can be implemented by means of a software system. 2) The conceptual quality is evaluated to prove that widely established reference models, e.g. EPC, Petri nets and UML-Diagrams, can be applied within the scope of our approach. 3)The economic quality is evaluated to prove the efficacy of our approach. The term “economic” in the context of designing Green IS is not associated with the financial value but rather with the utility of our approach, c.f. [ST14].

The Case: The publishing company runs a medium-sized datacenter to provide internal services for employees such as user profile hosting, email hosting and terminal/remote desktop services. Due to load changes, high overcapacities have been accumulated to provide constant accessibility. Consequently, the company faces high expenditures on IT infrastructures and overhead as well as high energy consumption. The company aims to replace its own IT (data center) infrastructures with cloud computing services. The outsourcing risks of a cloud migration have been estimated not critical. Also a leading position in the field of CO_2 aware business processes is aspired. As a first test, the layout system (application system) used within the editorial process to automatically arrange articles on a newspaper page was outsourced to a cloud computing provider. The client and data transfer energy consumptions remain the same for all alternatives so they can be neglected when comparing the different cloud computing alternatives. Three providers were selected for investigation:

- *Smart Cloud* offers Infrastructure as a Service using datacenters located in the US. The layout system is accessed via remote desktop applications. This datacenters run servers with a maximum energy consumption of 200 W and 200 Gigaflops maximum calculating performance. Measurements at the energy supply of the rack servers reveal an average consumption of 0.3 Wh/Terrafloating point operations (TFLO) at a utilization of 60 %. The power usage effectiveness (PUE) of the Smart Cloud datacenters equals 1.4.

2 *Online Edit* offers Software as a Service using datacenters located in Norway. The layout system is accessed via internet browsers. This datacenters run servers with a maximum energy consumption of 250 W and 300 Gigaflops maximum calculating performance. Measurements at the energy supply of the rack servers reveal an average consumption of 0.23 Wh/TFLO at a utilization of 65 %. The PUE of the Online Edit datacenters equals 1.4.

3 *Jour Edit* offers Software as a Service using datacenters located in Poland. The layout system is accessed via internet browsers. This datacenters run servers with a maximum energy consumption of 500 W and 800 Gigaflops maximum calculating performance. Measurements at the energy supply of the rack servers reveal an average consumption of 0.23 Wh/TFLO at a utilization of 50 %. The PUE of the Jour Edit datacenters equals 1.3.

The implicit factual model including the three alternatives as well as the editorial process is depicted in Figure 3.

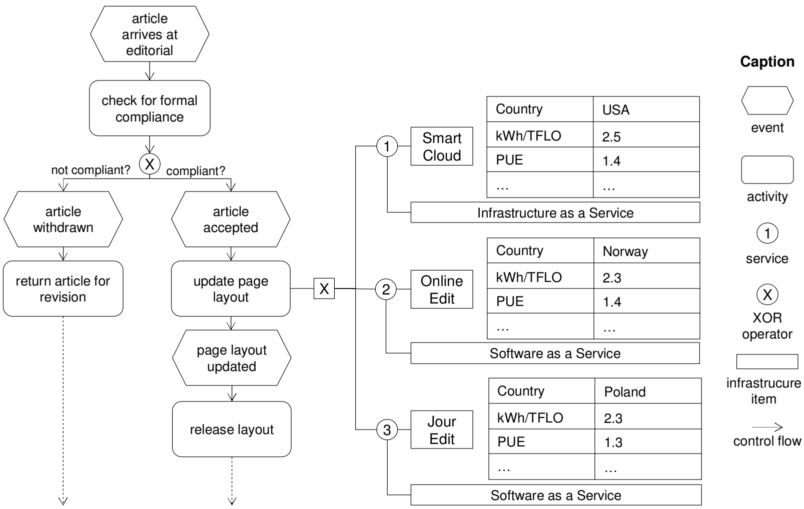

Figure 3 Factual model of different cloud computing service alternatives [BSS09]

To derive the environmental impact associated with the three design alternatives, inventory models are now developed. In this fictional case, we apply the commercial LCA software tool Umberto[1] for the implementation of petri-net based flow diagrams [Mu89]. Figure 4 depicts a simplified product system representing the cloud provider's use of electrical energy. On the right-hand side of the figure, the activity *update page layout* is depicted. The left-hand side shows the flows associated with the provided cloud function. The activity *cloud use* represents the use direct use of electricity (servers) as well as the use of facility functions (cooling, overhead). Direct energy consumption is

[1] www.umberto.de/en/

determined by the server's energy consumption (kWh/TFLO). Energy consumption caused by facility functions are represented by the activity *dc facility use* and are determined by the PUE of the datacenter. The activity *electricity, high voltage, production mix* represents consumptions and emissions associated with the production and distribution of the energy from raw material extraction to the datacenter. In our case we will use the life cycle database ecoinvent[2] to gather data for the physical flows associated with the production of electricity.

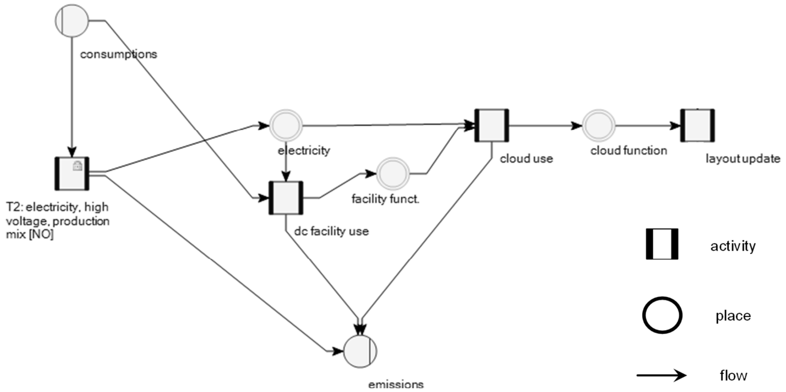

Figure 4 Simplified inventory model of cloud computing services

An impact model is calculated from the inventory model using the Umberto internal calculating engine. The impact model is depicted in Figure 5 in its short form, showing the environment impact of one hour service offered by the cloud provider *Online Edit*. CO_{2e}-emissions associated with the use of the service for one hour are depicted in line three (0.003 kg CO_{2e}). The services can now be compared based on the environmental impact model.

Product: layout post [A15 (layout update -> layout updated)] (1.00 unit)
LCIA Method: ReCiPe Midpoint (H) w/o LT - **agricultural land occupation** w/o LT, ALOP w/o LT: **2.62E-03 m2a**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **climate change** w/o LT, GWP100 w/o LT: **0.03 kg CO2-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **fossil depletion** w/o LT, FDP w/o LT: **7.40E-03 kg oil-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **freshwater ecotoxicity** w/o LT, FETPinf w/o LT: **3.17E-04 kg 1,4-DCB-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **freshwater eutrophication** w/o LT, FEP w/o LT: **6.94E-06 kg P-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **human toxicity** w/o LT, HTPinf w/o LT: **0.01 kg 1,4-DCB-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **ionising radiation** w/o LT, IRP_HE w/o LT: **1.04E-03 kg U235-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **marine ecotoxicity** w/o LT, METPinf w/o LT: **3.18E-04 kg 1,4-DCB-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **marine eutrophication** w/o LT, MEP w/o LT: **6.00E-06 kg N-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **metal depletion** w/o LT, MDP w/o LT: **6.76E-03 kg Fe-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **natural land transformation** w/o LT, NLTP w/o LT: **3.45E-05 m2**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **ozone depletion** w/o LT, ODPinf w/o LT: **2.46E-09 kg CFC-11-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **particulate matter formation** w/o LT, PMFP w/o LT: **8.32E-05 kg PM10-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **photochemical oxidant formation** w/o LT, POFP w/o LT: **1.25E-04 kg NMVOC**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **terrestrial acidification** w/o LT, TAP100 w/o LT: **1.31E-04 kg SO2-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **terrestrial ecotoxicity** w/o LT, TETPinf w/o LT: **2.28E-05 kg 1,4-DCB-Eq**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **urban land occupation** w/o LT, ULOP w/o LT: **1.00 m2a**
LCIA Method: ReCiPe Midpoint (H) w/o LT - **water depletion** w/o LT, WDP w/o LT: **1.08E-04 m3**

Figure 5 Shortened environmental-impact model of *Online Edit*

It can be stated that: 1) the software can be implemented by means of a software system, e.g. using LCA software tools, 2) widely established reference models, e.g. EPC or Petri nets, can be applied within the scope of our approach, 3) the approach fulfils its purpose to compare different design alternatives according to their environmental impact.

[2] www.ecoinvent.ch

5 Conclusions and Research Outlook

Developing an environmental sustainable society is one of the major challenges of our time. Researchers from various disciplines aim to develop sustainable products, services, behavior patterns and organizational systems. The IS discipline is now called on to contribute its share to this challenge by assessing the environmental impact of information systems and by designing new sustainable alternatives for current systems. One of the most promising concepts investigated by IS research is cloud computing. Despite being a young and still emerging field in IS research, recent publications have confirmed its potential to reduce the environmental impact of information systems. The life cycle impact modelling approach constitutes a first step towards an environmental oriented design of information systems. It offers IS designers the ability to forecast the environmental effects of their decisions. This ability will be indispensable to the design of more sustainable information systems. Due to our research approach, there are some specific limitations to this work. The evaluation builds on a single fictional case. This strategy was considered useful to demonstrate the fundamental features of our results. However, the question of whether other modelling languages and software tools besides the applied ones can be used within the approach remains unanswered. Due to the strict word limit, it was also not possible to give a deeper introduction into the development of inventory models. We suggest that interested readers consult related work on LCA [Fi09, Gu02]. The presented results may be thought of as a snapshot within the iterative design science research process. Further iterations and evaluations within real-world scenarios will performed to further refine the approach. The chosen metrics in section 4 should be recognized only as an example for demonstration purposes. Metrics like PUE or carbon usage power usage effectiveness should always be regarded in relation to performance-based metrics like TFLO. Acknowledging the limitations of this work, future research questions could include: Which modelling languages and software tools can be applied within the frame of the life cycle impact modelling approach? How can the approach be presented to business partners? Does the impact model contain enough information to support decision making? What are possible usage scenarios besides cloud computing? In the next step, business partners will be involved in expert interviews and case studies. Experiments on the behavior of decision makers will be conducted to investigate how environmental impact data is used for decision making.

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