Weighting Environmental Impacts in Software Distribution Systems

Bertrand Ithurburn, *Member, IEEE,* Birgit Penzenstadler, *Member, IEEE*

Abstract—Developers and analysts who try to create environmentally sustainable systems occasionally compromise by reducing one environmental impact while increasing another one. Certain products save energy but produce dangerous material when an energy-inefficient alternative design would not. These products reduce consumption at the expense of introducing toxic substances into the environment. To deal with these tradeoffs, researchers, such as Patrick Hofstetter, have developed weighting metrics to account for every type of impact in a single assessment. However, a weighting metric has the potential to direct design toward neglecting lowly weighted impacts in order to address highly weighted ones. This study aims to clarify the effects of different weighting configurations. The project employs Hofstetter's mixing triangle, which weights three different areas of environmental impact against each other. It compares the effects of an application service provider to the effects of a system that uses locally hosted software. The comparison uses multiple weighting configurations. The results suggest that climate change has a greater impact than any other environmental effect.

Index Terms—Centralized control, decentralized control, green computing, green design, product life cycle management, requirements engineering, sustainable development.

1 Introduction

PRODUCT designers concern themselves with protecting the environment [1] [2], but how do these designers quantify the impacts their products make? Researchers have made multiple metrics to address this issue [3] [4] [5], but these metrics have some complications. Specifically, when designers attempt to reduce a certain type of environmental impact, they might increase their impact in another way [6] [7] [8]. This situation would not present a problem if designers could reduce particular impacts without increasing others, but many green product designs unintentionally contribute to environmental degredation in areas that fell outside the scope of the designer's concerns. Specifically, energy-efficient products often achieve their lower uses of energy by using designs that produce dangerous waste. Such products include solar panels, compact fluorescent lamps (cfl), and rechargeable batteries. Each one of these products use less energy than their common alternatives, but each one also produces more toxic material than their energy-inefficient alternatives do [6] [7] [8].

If designers focus exclusively on one type of environmental impact, such as energy use, they run the risk of increasing damage in another way. The preceding examples suggest that designers have focused their efforts on energy use and ignored dangerous material. In the process, some of the energy-efficient designs have actually increases the quanitity of toxic content in the environment. If this pattern persists too much, then dangerous material, or some other ignored domain, could become more of a problem. For this reason, analysts have motivation to use measurements of environmental damage that capture the entirety of a product's impact.

As such, the tools that analysts use ideally will capture all environmental impacts of a product. Some analysts already use such tools [11], but these techniques have limitations. For example, some methods use weighting to account for different dimensions of environmental impact. The next paragraph describes this process.

To illustrate the weighting process, imagine an analyst has two value categories, one that quantifies energy use, and another that quantifies mercury released into the environment. The analyst has two different product designs. One design uses less energy, but the alternative produces less mercury. As a side note, this tradeoff describes the relationship between CFL and traditional light bulbs. The analyst has four values: the energy used by design 1, the mercury produced by design 1, the energy use by design 2, and the mercury produced by design 2. The analyst cannot simply conclude that one design has less impact than another, nor can the analyst simply add numbers together since they describe things with different consequences per unit. To resolve this issue, the analyst first normalizes the numbers to a common scale and then weights them such that the resulting values reflect the overall damage caused by either the energy use or mercury produced. The analyst can then add the energy number to the mercury number to get a final value that communicates the total damage of a design. The analyst now has a way to determine which design causes more harm.

This approach allows an analyst to account for multiple

- *This paper is based on the first author's Master of Science thesis.*

- *B. Ithurburn was with the Department of Computer Engineering and Computer Science, California State University, Long Beach, CA 90840 USA. He is now with the Department of Computer Science, The Graduate Center at City University of New York, NY 10016 USA.*
  E-mail: bithurburn@gradcenter.cuny.edu.
- *B. Penzenstadler is with the Department of Computer Engineering and Computer Science, California State University, Long Beach, CA 90840 USA.*
  E-mail: birgit.penzenstadler.csulb.edu.

dimensions, but it introduces subjectivity into the analysis. The weighting step involves a judgment on how much damage each type of impact causes. As such, this step can allow an analyst to focus on some impacts to the exclusion of others.

This paper does not attempt to resolve the issue of the proper way to weight impacts. Instead it looks at how different weighting configurations would affect design decisions. In the previous example, a configuration that heavily weights energy use would likely favor design 1, while a configuration that heavily weights toxic waste would likely favor design 2. This paper seeks to investigate how this weighting process affects design decisions, if it has a significant effect at all. Perhaps weighting has a negligible effect on how different designs appear to damage the environment. However, if the effect proves significant, then analysts may want to consider what their assessment techniques mean for environmental impacts.

This paper focuses on tools that companies most widely use. For examining the entire life cycle of a product, analysts worldwide most commonly use the software programs SimaPro and GaBi [9], both of which extend the Life-Cycle Assessment (LCA) technique to examine a product's entire life cycle. LCA does not refer to a specific type of software. It refers to a process documented by the International Organization for Standardization (ISO) [3] [4]. Using LCA means abiding by the guidelines laid out by the ISO. To use LCA, analysts will often employ software, and they will typically use either SimaPro or GaBi. Both products evaluate multiple types of impacts by including methods to normalize and weight the results, so they allow an analyst to assess total impact in a single number [5] [10]. GaBi bases their weights on questionnare results from 245 experts on environmental impacts [5]. SimaPro includes a triangle tool that allows the user to set weighting values [10]. This paper focuses on the effects different weighting methods can have on analysis, so the authors employ SimaPro's weighting triangle tool instead of GaBi's technique.

The triangle comes from Hofstetter et al.'s research [11]. Accordingly, this paper uses Hofstetter et al.'s triangle for the weighting configurations. This use entails using the triangles three impact categories: human health (HH), ecosystem quality (EQ), and resource use (RU) [11].

The impact categories come from Eco-Indicator 99, an extension to LCA. Like LCA, Eco-Indiator 99 refers to a process defined as a series of standards [12]. SimaPro implements these standards to normalize its LCA data [10]. LCA has an optional phase called the Life-Cycle Impact Assessment (LCIA), which provides additional information for the interpretation of LCA results [4]. Eco-Indicator 99 offers one possible way to implement the LCIA. In this paper, LCIA refers to using Eco-Indicator 99 to normalize the data and using the weighting triangle to weight the normalized data.

To summarize, this paper examines how weighting environmental damage affects product design. To accomplish this task, the authors use LCA as the example environmental metric because of its commonality. Eco-Indicator 99 extends LCA by normalizing the data, and the weighting triangle allows an analyst to account for all of the different effects at once.

In order to examine these metrics, the authors use a case study that involves two systems that use different means to distribute software. One system distributes software through centralized means with data centers and thin clients. The other distributes it through decentralized means by allowing users to install the software on their locally hosted systems. This case study has several advantages. It presents a genuine conflict between viable options that companies can and do choose between [14]. One model does not have an obvious environmental advantage over the other one. Most importantly, the two models differ on a fundamental design conflict: centralization versus decentralization. This conflict allows the paper to investigate the following research question: How do weighting configurations affect system design? With this case study, the paper can shed some light on whether one design principle offers any environmental advantage over its alternative and if that advantage rests on a particular weighting configuration.

This study has a second research question. Do different environmental impacts correlate with each other in computer system design? Do engineers need to consider tradeoffs among effects? In an ideal situation, they would not. Perhaps computer systems do not have the same problems that other green technology has. Just because some technology, such as a compact fluorescent lamp, saves energy at the cost of introducing dangerous physical material, it does not mean that computer systems must make the same compromise.

To answer these questions, this paper documents the LCA results for the two aforementioned product designs. The LCA will use multiple weighting configurations in accordance with Hofstetter's mixing triangle to see the effect that weighting has. The results suggest that changing the weighting configuration has little effect on design outcomes for these two product designs. The results also suggest that climate change has a greater environmental impact than any other environmental consequence. The remainder of the paper discusses the implications of the results, the limitations of the research, and avenues for future study.

2 Background

Past research has analyzed the environmental consequences of computer systems. This Section includes an introduction to the theoretical foundations for environmental analysis and system design found in this research. It then summarizes the similarities and differences among the literature.

2.1 Theoretical Foundations

Ecological sustainability serves as a foundation for green technology and forms one of the three pillars of sustainability theory as documented by the United Nations General Assembly [15]. The other pillars, economic and social sustainability, do not factor into this study, so the analysis will focus exclusively on environmental consequences. Ecological sustainability has two perspectives. One perspective focuses on sustaining the environment for the sake of humans, and the other focuses on sustaining the environment for the sake of the intrinsic value of the natural world. This study contains elements of both perspectives.

The review now turns to the relationship between environmental impact and centralized system design. Centralization and decentralization show up in multiple places in the world of computer systems. Choosing between centralized and decentralized designs shows up in fields such as operating systems and file sharing, among others. When assessing environmental effects, past research, such as D. Maga, M. Hiebel, and C. Knerman's "Comparison of two ICT solutions: Desktop PC versus thin client computing," has found that centralized systems have smaller impacts [14]. Decentralized systems often use more hardware than their centralized alternatives, and the amount of hardware tends to positively correlate with energy use. However, the studies on this subject have not definitively shown the consistently smaller impact of either design.

Different types of environmental consequences do not always correlate. These three articles—"Environmental impacts from solar energy technologies" by T. Tsoutsos, N. Frantzeskaki, and V. Gekas, "Comparison of life-cycle analyses of compact fluorescent and incandescent lamps based on rated life of compact fluorescent lamp" by L. Ramroth, and "Used lithium ion rechargeable battery recycling using Etoile-Rebatt technology" by D.-i. Ra and K.-S. Han—show the unintended consequences of green products. Solar panels, compact fluorescent lamps, and rechargeable batteries all save energy, but they also all produce dangerous material [6] [7] [8]. An analyst must decide whether these products help or hurt the environment relative to their alternatives. With computer systems, studies will often prioritize energy at the expense of other environmental considerations [14]. Researchers can quantify energy in well-understood units, which makes it a convenient point of focus. Other environmental consequences, such as ecotoxicity, do not translate into quantities as easily. Computer systems have components that cause acidification and eutrophication, so when analysts focus exclusively on energy, they overlook other relevant elements.

Aside from ignoring certain types of environmental effects, analysts also occasionally ignore relevant processes involved in the system. As described by H. Mathews, C. Hendrickson, and D. Matthews in the book *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter*, researching the environmental effects of systems involves setting a system boundary, and that boundary may leave factors like transportation or energy production outside of the system's scope [16]. Researchers often must compromise because they do not have access to all of the relevant data. However, neglecting these processes can distort results. For example, an assessment of a data center's environmental impact might define the use of cooling water outside of its scope. A cooling system can contribute significantly to the overall system's environmental effects, and the assessment might reach an inaccurate conclusion because of the omission. Ideally, researchers will include as much of the relevant information as possible.

Defining system boundaries exemplifies one of many ways that environmental analysis has value judgnments. At a fundamental level, concern for the environment implies valuing it. Additionally, assessing environmental impact entails other value judgments like how much value to place on human well-being in relation to ecological preservation [12]. This study does not aim to resolve any conflicts between values. It only aims to inform about how different methodologies determine system design. Specifically, weighting different environmental consequences inevitably involves value judgments. While this paper examines how weighting can dictate design choices, it does not recommend any particular way of weighting.

2.2 Commonalities and Differences in Existing Literature

Environmental impact studies often recycle data, as shown by H. Gloge in the articles "Thin clients 2011: Ecological and economic aspects of virtual desktops" and "Environmental comparison of the relevance of PC and thin client desktop equipment for the climate, 2008" and by D. Maga, M. Hiebel, and C. Knermann in their article [2] [1] [14]. Due to a dearth of easily attainable information, analysts have to use flawed data. Researchers note the age of the data in their studies because they cannot find recent information [14] [2]. A. Jönbrink shows in "Lot 3 personal computers (desktops and laptops) and computer monitors" that when able, researchers use data from direct measurements [17]. However, they often cannot use direct measurements. Consequently, when a paper uses primary information, the data in the paper then show up in subsequent studies [14] [1]. Researchers ideally only go to secondary sources if they must, and they often must go to secondary sources. In the case of LCA studies, practitioners have established a hierarchy of data that privileges direct measurements above databases and databases above other studies [16]. In spite of this hierarchy, researchers can rarely avoid using data sources low on the hierarchy.

Since many studies use similar, occasionally identical, data, they frequently reach similar conclusions. For example, past research has consistently found better environmental performance among systems that use thin clients when compared to systems that use desktop computers [14] [1]. Systems based on thin clients use less energy and smaller quantities of physical material. For example, one study that used a full LCA found lower quantities of physical material and energy for the thin client system [14]. Other researchers using different methods have tested versions of desktop systems against their client-server equivalents, and the results consistently favor systems that use thin clients [2].

The studies that use LCA as their method of analysis often use it because of its cradle-to-the-grave approach [4]. Cradle-to-the-grave means that the analysis covers the following phases: raw material acquisition, production, use, and end-of-life treatment. However, not every assessment uses the cradle-to-grave approach. Some LCAs use a cradle-to-gate approach, which means that the analysis starts at material acquisition and ends after production [3]. This type of analysis neglects phases, such as disposal, that may alter the results of an analysis. Transportation can also go missing from these analyses, which happens in both cradle-to-gate and cradle-to-grave LCAs.

Furthermore, studies occasionally neglect to account for the tangential effects of energy production [14] [2] [17]. The quantity of energy used might appear, but the analysis will not necessarily capture the full impact. More specifically, some studies do not specify the source of energy, and the source of energy can greatly affect the overall consequences. For example, nuclear energy yields a different set of consequences than energy produced by fossil fuels. Energy production involves transportation, disposal, and material extraction of its own, and these processes differ if the source is nuclear or if it comes from fossils. Ignoring tangential processes potentially has a nontrivial impact on the overall results.

Researchers vary on how they treat data limitations. LCA manuals, such as J. Guinée et al.'s *Handbook on Life Cycle Assessment*, explain ways to ensure data validity [18] [16] [3] [4]. A comprehensive LCA will theoretically have a completeness check, a sensitivity check, a consistency check, and a third party report. Realistically, not all studies can include these steps. In principle, these processes assure that the LCA produces worthwhile results, but in practice, they demand so much from the researchers that steps inevitably get neglected. As an example, not every practitioner has access to LCA experts, and the LCA guidelines recommend one be consulted [4]. The level of rigor involved in an ideal LCA keeps it from being practical for everyone.

2.3 Identified Research Gap

Government organizations set standards for technology, and engineers need to design systems that conform to these standards. These regulations do not exempt computers. For example, as written by Dunkin in *Personal Computer Configuration and Management Standard*, the Environmental Protection Agency of the United States asks that people and organizations purchase computers and monitors that have Energy Star compliance [19]. And if designers must make tradeoffs in order to comply, then weighting of impacts will affect the resulting products and, in turn, their impacts on the environment. Research on weighting can help illuminate these ramifications.

3 Method

This article documents the life cycle assessment of two computer systems that perform similar functions through different means. LCA refers to a method of measuring the environmental consequences of a product throughout the product's lifetime [3] [4]. The LCA in this article will cover two systems. The first delivers software by way of an Application Service Provider (ASP). The second distributes the same software for local hosting. The LCA results then go through Eco-Indicator 99 [12], a method for quantitatively assessing the damage of the systems. The Eco-Indicator results include the impact categories used by a weighting triangle that aggregates the results into a single score [11]. Due to constraints on article length, many of the steps of a comprehensive LCA do not appear in this article.

For the purposes of this study, the software SimaPro offers the most comprehensive means of conducting the LCA. However, due to financial constraints, this study could not employ SimaPro in its entirety. Instead, the authors used the normalization and weighting elements of SimaPro, which are Eco-Indicator 99 and the weighting triangle, with OpenLCA, a free software implementation of LCA [13]. OpenLCA includes Eco-Indicator 99's normalization factors. As for weighting the results, the authors performed this step without the assistance of software.

The LCA begins by explaining its goal and motivations, which include reasons for using LCA and the study's starting points. It then sets the scope of the analysis. For LCA, the scope explains the study's assumptions, and it includes explanations for a functional unit, the system boundary, and the types of data. A functional unit provides a way to quantitatively describe performance of the systems. The system boundary determines which processes will go in the study and which will not. The types and sources of data Section communicates from where and how the researchers obtained the data. The LCA continues with a Section that explicitly relates the data to the functional unit. After this part, the paper presents the LCIA, in which the researchers use Eco-Indicator 99 to divide the impacts into categories and normalize the data. The LCA concludes by weighting the normalized values.

3.1 LCA Goal

This LCA aims to compare an ASP to a system of locally hosted software. The comparison can reveal how environmental considerations affect system design, and engineers can use this information to design sustainable systems. The LCA focuses on these three impact categories: HH, RU, and EQ. Eco-Indicator 99, which the assessment phase of this LCA employs, uses these three categories. Although the LCA's goal involves a comparison, it does not include declaring the superiority or equivalence of one product in relation to the other, although a reader may draw such a conclusion from it. As such, the goal does not constitute a comparative assertion disclosed to the public as defined in the LCA standards [18].

The LCA approach provides a thorough evaluation of the effects that the ASP and the distributed system might have on living beings, and it allows for comparisons with multiple weighting configurations. However, it has limitations. This LCA does not provide a financial understanding of environmental effects. Nor does it address localized impacts, dynamic complications, or social costs. Furthermore, data availability, constrained by the authors' budget, limits the certainty of the assessment.

This study assumes all of a traditional LCA's starting points as defined in the handbook [18]. The first two points demand that the LCA focus on change oriented, structural decisions and on the main function of the products. These foci imply that the study does not concentrate on any particular process, chemical, impact, country, or year. By not concentrating on any of these particular components, the LCA fulfills the third starting point's criterion, which states that the LCA not pay special attention to a particular component.

Finally, this LCA does not prescribe any action based on any differences found between the two systems. The study aims to inform, not recommend.

3.2 LCA Scope

The LCA has two product systems. They produce the same software product. This product keeps and maintains Electronic Health Records (EHR). The LCA uses this particular type of software because developers regularly have to decide whether to implement EHRs as ASPs or locally hosted systems, as seen in the online articles "Hosted EHR vs. server based" and "What are the disadvantages and advantages of ASP vs. locally hosted?" [20] [21].

The LCA's data have an age range of approximately five to twenty years. The data sources dictated this range. Data collection took place over a six month period from 2015 into 2016. However, the researchers discarded most of the data acquired in the early months as unusable. Due to the study's financial constraints and a lack of access to primary sources, the National Renewable Energy Laboratory's (NREL) free Life-Cycle Inventory (LCI) Database provides most of the LCA's data. According to the database's guidelines, titled *U.S. LCI Database Project: User's Guide*, as of 2014, the database's content has an average age of five to six years [22]. The rest of the data came from reports that use a technique called a Methodology for Eco-design of Energy-Using Products (MEEUP). The MEEUP analyses use data that range from five to ten years in age [2] [17]. The collection and writing of the LCA occurred over the course of an academic year. This situation imposed limits on the collection. A longer period of time would likely have yielded more accurate information.

The LCA assumes that the two systems remain in use for five years, which matches the time period used in one of the primary data sources [2]. To keep the numbers close to the measurements from primary sources, the LCA sticks with the source's time frame.

The NREL LCI Database uses information from the United States, and the two MEEUP analyses use data from Europe [22] [2] [17]. As such, the LCA's geographic coverage does not go beyond these two regions. Alternative databases, such as Ecoinvent and GaBi, have a global scope, but they incur costs that exceed the budget of this study [16].

This paper assumes a level of technology from approximately 2011. Much of the data come from that particular year [2]. The thin client data has not aged quite as much as the information for the other machines. Specifically, the distribution and manufacturing data for the servers and desktop computers come from 2007 [17]. More recent data either did not exist in the proper form for LCA at the time research took place or cost too much for the researchers to access.

The study's economic processes cover all material taken from and expelled into the environment during the materials extraction, manufacturing, transportation, use, and disposal phases of the systems. These processes do not focus on the systems' primary product because the product is software and not a physical object in need of disposal.

In keeping consistent with the economic processes, the study's environmental interventions include all substances that enter or leave the system. The environmental inputs include water and coal. The outputs include carbon dioxide, sulfur dioxide, particulates, phosphate, nickel, mercury, dioxins, furans, volatile organic compounds, and general waste, both hazardous and nonhazardous.

This LCA uses a simplified level of analysis. No one will implement the products, and the researchers have limited resources. This latter detail precludes a higher level of sophistication, and the former suggests that the assessment does not need a more sophisticated analysis. The researchers only intend to illustrate how environmental considerations, mainly weighting of environmental impacts, affect system design.

In describing the functional unit, the question of why these two system designs, ASP and local hosting, suit the study. The assessment does not consider every possible system. Alternatives include Software as a Service (SaaS) models and Local Area Networks (LAN). The study excludes these options because it has a goal of answering questions regarding the advantages of centralized and decentralized systems. SaaS does not fit into either one of these categories as comfortably as ASP does for centralized and distributed software does for decentralized. LAN systems offer an intermediate option, so they do not work for testing the differences between the extremes. As a consequence of these exclusions, the assessment fdoes not account for any advantages SaaS or an intermediate option might offer.

3.2.1 Functional Unit

Both systems provide software as their primary functions. As such, the LCA defines the functional unit as a single work day of software use.

The LCA defines its reference flow as 130 users each using the software over a five-year period. For the ASP, this flow requires ten blade servers and thirteen thin clients per server [2]. For the distributed system, this flow requires 130 desktop computers.

3.2.2 System Boundary

In this LCA, the product systems for software distribution include any substance or energy that comes from or enters the environment. These substances and energies enter and leave without previous human transformation. Any transformation of the raw materials functions as part of a system.

The LCA models each system as a sum of foreground and background processes. The ASP's foreground system refers to the interactions of the servers and clients. The ASP's background system includes the manufacturing of hardware parts, materials extraction, transportation, and disposal. The distributed software system's foreground includes the use of computers to run the software. Like the ASP, its background system includes materials extraction, manufacturing, transportation, and disposal.

Due to the limitations in NREL's LCA database, the LCA does not include all flows that cross the system boundary [22]. For example, most of the processes in both systems use process water, but the process water flow available in the database lacks an accompanying unit process in the database to document its inputs and emissions.

3.2.3 Types and Sources of Data

This LCA does not have primary data. To reiterate, its data sources include two previous research papers and the NREL's LCI database. Both of the two papers use results from a MEEUP performed on computer products. As explained by R. Kemma et al. in *MEEUP Methodology Report*, a MEEUP entails recording the emissions and materials used in a product's lifetime [23].

TABLE 1
The Inputs and Outputs of the MEEUPs

inputs	waste outputs	air outputs	water outputs
energy process water cooling water	hazardous waste nonhazardous waste	GWP AD VOC POP HM PAH PM	metals EUP

TABLE 2
Mapping of the MEEUP Categories to NREL Data

MEEUP category	NREL category	Flow type
energy	electricity	product
process water	process water	product
cooling water	cooling water	elementary
hazardous waste	hazardous waste	waste
nonhazardous waste	nonhazardous waste	waste
GWP	carbon dioxide	elementary
AD	sulfur dioxide	elementary
VOC	VOC	elementary
POP	dioxins and furans	elementary
HM	nickel	elementary
PAH	nickel	elementary
PM	particulates	elementary
metals	mercury	elementary
EUP	phosphate	elementary

The results in the two MEEUP papers track three types of inputs for most processes: energy, process water, and cooling water. For general waste, the papers divide the outputs into hazardous and non-hazardous categories. For outputs to air, the MEEUPs recorded the following: Global Warming Potential (GWP), Acidification potential (AD), Volatile Orgranic Compounds (VOC), persistent organic pollutants (POP), heavy metals (HM), polycyclic aromatic hydrocarbons (PAH), and particulate matter (PM). For outputs to water, the MEEUPS record metal and eutrophication potential (EUP) [2] [17]. Table 1 summarizes this information.

The other data source, the NREL database, must integrate with these papers to complete the LCA. The papers on their own do not offer all of the information needed. For example, the papers do not account for the consequences of producing electricity, though they do account for electricity as a final product. The database does not have the same categorization scheme as the papers. To make them work together, the categories of the papers map to flows in the database in some way. In other words, each category in the paper must belong to some catgory in the database. The mapping appears in Table 2. Most of the categories do not perfectly match their substitutes. For example, acidification potential can change because of material other than sulfur dioxide, such as nitrogen oxide. However, the MEEUP data do not communicate which particular substances cause the acidification potential to increase, so the LCA assumes sulfur dioxide causes all of the acidification potential. In this manner, the LCA uses the closest approximation available in the database for every category in the MEEUP research.

Table 2 also classifies each entry by its flow type. Definitions of the flow types follow. Elementary flow describes material or energy entering the system from the environment without previous human tranformation. Product flow describes something the enters from another system or leaves to another system. Waste flow describes substances that will go through a disposal process [4].

The process water category complicated the analysis. The LCA classifies process water as a product flow because a process must prepare it for use by deionizing it. However, the database does not have a corresponding process for this product, so the LCA does not have the data to account for the process of creating process water. As such, process water affects the results as if it were an elementary flow.

TABLE 3
Time and Energy for Each Mode over a Five Year Period

Product	Softoff h	Use h	Softoff energy	Use energy
Thin client	33 900	9900	1.9 W	11.5 W
Desktop pc	28 400	15 400	0 W	33.4 W
Blade server	33 900	9900	144.7 W	149.1 W

TABLE 4
Total Energy Use Over Five Years

Product	Energy per machine	Energy per system
Thin client	641.736 MJ	83 425.69 MJ
Desktop pc	1850.112 MJ	240 514.56 MJ
Blade server	647.5392 MJ	6475.392 MJ

3.3 Relating Data to the Functional Unit

To reiterate, this LCA defines its functional unit as a single work day of software use. Based D. Maga, M. Hiebel, and C. Knermann's article, the LCA treats a single work day as running a thin client or desktop computer for nine hours a day [14]. Based on the same research, the LCA treats a year as having 220 work days.

To figure out the amount of energy expended by workers, the LCA distinguishes between two modes of operation: use and softoff. Softoff refers to a state of low power consumption, either standby mode or a complete shut down. For thin clients, softoff machines generally still consume power. For desktop computers, softoff mode often means zero consumption [2]. Table 3 displays how many hours each type of machine spends in each mode over a five-year period. Because of their functional relationship, the server and thin client have the same hours.

The desktop computers have more use hours because, in practice, users usually switch off thin clients at night, but only 30% of users switch off desktop computers [2]. Theoretically, the use hours might equal each other for both machines, but real life users treat the machines differently. This LCA aims to reflect reality, so it uses the numbers from real users.

Table 4 shows the complete energy use for the three types of machines over five years. The values in the middle column refer to the energy use of individual machines, and the right column shows aggregate energy use for all of the machines combined.

Fig. 1 provides a graphical representation of the data in the middle column of Table 4. The disparity among the machines shows how much more the desktops consume. The greater number of use hours for the desktops has a significant effect.

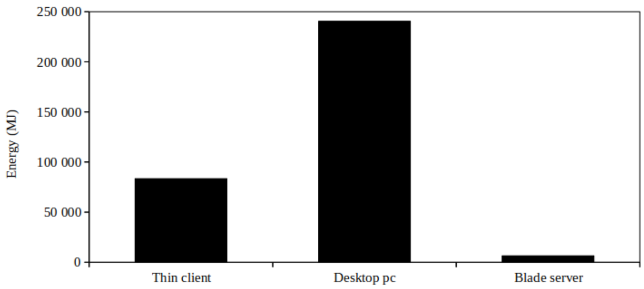

Fig. 1. Total energy use of each machine over a five year period.

The reference flow has 130 users. Each server provides operations for thirteen thin clients. Consequently, the ASP has 130 thin clients and ten servers. The system of locally hosted software has 130 desktop computers. Multiplying the numbers in the middle column by the number of machines produces the numbers in the rightmost column in Table 4.

3.4 Life Cycle Impact Assessment (LCIA)

This Section begins with a review of the LCIA details. In this particular study, the LCIA uses Eco-Indicator 99. Eco-Indicator 99 has three impact categories: HH, EQ, and RU [12]. Each impact category has its own subcategories. For HH, the subcategories include climate change, ozone layer depletion, carcinogenic effects, respiratory effects, and ionizing radiation. For EQ, the subcategories include eco-toxicity, acidification, eutrophication, and land use. For RU, the subcategories include surplus energy from fossil fuels and minerals.

Alternative impact categories and indicators exist, but they do not serve this paper's needs as well. This study analyzes the consequences of weighting different environmental impacts. Since the chosen tool for assigning weights, the mixing triangle, uses Eco-Indicator 99, this study's LCA also uses Eco-Indicator 99, including its impact categories and category indicators [11] [12].

Eco-Indicator offers three perspectives for characterization: individualist, hierarchist, and egalitarian. This LCA uses the individualist perspective because it has a shorter time perspective than the other two options According to M. Goedkoop and R. Spriensma in *The Eco-Indicator 99: A Damage Oriented Method for Life cycle Impact Assessment*, for the hierarchist and egalitarian perspectives, the calculations continue until the simulation reaches a steady state [24]. This LCA does not need such a long time frame, so it uses the shorter time horizon assumed by the individualist perspective.

Each impact category has its own characterization factors. For HH, the individualist characterization model uses concentrations from emission flows over a period of 100 to 200 years [24]. The following presents the sources of the characterization factors for HH's subcategories. For carcinogenics, the model only uses substances that the International Agency for Research on Cancer (IARC) considers to have sufficient evidence of carcinogenicity. For respiratory emissions, the characterization varies for each substance, but they all come from calculations in P. Hofstetter's *Perspectives in the Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere* [25]. The global warming information comes from multiple sources by the same author. Specifically, the climate change model derives its estimates from what R. Tol calls General Circulation Models, as documented in Tol's "Estimates of the damage costs of climate change part 1: Benchmark estimates" and "Estimates of the damage costs of climate change part 2: Dynamic estimates" [26] [27]. The final HH subcategory focuses on ozone. For ozone layer depletion, the characterization model uses a hundred year time frame to create equivalency factors as documented in M. Hauschild's and H. Wenzel's *Environmental Assessment of Products Volume 2: Scientific Background* [28].

Ecosystem quality has two characterization categories relevant to this LCIA. The first one focuses on ecotoxicity. The European Union System for the Evaluation of Substances provides a model for the toxicity of each relevant emission, as documented in T. Vermeire et al.'s article, "European Union system for the evaluation of substances (EUSES). Principle and structure" [29]. The other characterization category addresses acidification and eutrophication. This latter category uses the percentage of plants likely to disappear, as calculated on a European scale by the Ministry of Housing, Spatial Planning and the Environment [12].

The mechanism by which Eco-Indicator 99 assesses an impact involves taking the relevant environmental flows and characterizing them as a quantity with a particular unit. For example, a few of the processes release carbon dioxide into the environment. This carbon dioxide has relevance to the climate change subcategory and its containing HH impact category. Every relevant flow has a characterization factor assigned to it based on the size of its impact. Carbon dioxide has a characterization factor of 0.013333 $\frac{\text{DALY}}{\text{kg}}$. These characterization factor numbers come from the characterization the sources in the preceding paragraphs of this Section. To characterize the values, the researchers multiply the factor by the amount of carbon dioxide to quantify how much it contributed to the category.

Due to the scale of the task, not every flow in the systems entered into the assessment. The researchers had to enter every individual flow into Eco-Indicator from NREL's database, but the large quantity of flows made including all of them unrealistic for the time allotted.

Table 5 shows the characterization factors for the elementary flows output by the processes derived from the MEEUP analyses. For the sake of space, the table uses the synonymous phrase "impact factor" in place of "characterization factor" in the table's header. However, the impact factor for coal does not come from Eco-Indicator's data. The researchers fabricated this value because OpenLCA's available Eco-Indicator data do not have any fossil fuel information to use as a point of comparison. The other values in the table come from finding equivalent flows in OpenLCA's default Eco-Indicator data.

3.5 Normalization

The OpenLCA implementation of Eco-Indicator 99 provides normalization values. The normalization numbers come from a reference value calculated by the following formula from T. Blonk et al.'s *Drie Referentieniveau's voor Normalisatie*

TABLE 5
Characterization Factors

Flow	Subcategory	Category	Impact factor
CO_2	Climate change	HH	$0.013333 \frac{\text{DALY}}{\text{kg}}$
Coal	Fossil fuel	Resources	$1.0 \frac{\text{MJ}}{\text{kg}}$
Dioxins and furans	Ecotoxicity	EQ	$132000 \frac{\text{PDF} \cdot \text{m}^2 \cdot \text{yr}}{\text{kg}}$
Mercury	Ecotoxicity	EQ	$19.3 \frac{\text{PDF} \cdot \text{m}^2 \cdot \text{yr}}{\text{kg}}$
Nickel	Ecotoxicity	EQ	$90.6 \frac{\text{PDF} \cdot \text{m}^2 \cdot \text{yr}}{\text{kg}}$
Nickel	Carcinogenics	HH	$0.00679 \frac{\text{DALY}}{\text{kg}}$
Particulates	Respiratory effects (inorganic)	HH	$2.74 \cdot 10^{-4} \frac{\text{DALY}}{\text{kg}}$
SO_2	Acidification and eutrophication	EQ	$1.041 \frac{\text{PDF} \cdot \text{m}^2 \cdot \text{yr}}{\text{kg}}$
VOC	Respiratory effects (organic)	HH	$6.0 \cdot 10^{-7} \frac{\text{DALY}}{\text{kg}}$

TABLE 6
Normalization Factors for Each Impact Category

Impact category	Normalization factor
Ecosystem quality	5605.3811659
Human health	0.00465332713
Resources	347.46351633

in LCA [Three Reference Levels for Normalization in LCA] [30] [24].

$$E_t = P_t \cdot \frac{E_k}{P_K} \tag{1}$$

The definition of each variable follows.

$$E_t \equiv \text{Total emission in Europe} \tag{2}$$

$$P_t \equiv \text{Total energy use in Europe} \tag{3}$$

$$E_k \equiv \text{Known emission} \tag{4}$$

$$P_k \equiv \text{Energy use of countries with known emissions} \tag{5}$$

Table 6 summarizes the values that result from this calculation. The numbers come directly from the OpenLCA LCIA database, so this study uses the same number of significant figures as the database.

3.6 Weighting

This LCA uses multiple weighting configurations. The configurations compromise between HH, EQ, and RU. The three weighting factors, one for each impact category, must add up to 100% [11]. The researchers multiply the factors by the corresponding numbers that represent the impact for each of the categories.

4 Results and Discussion

The LCA concludes by presenting the results from the LCIA in raw, normalized, and weighted forms. Then it moves into an interpretation phase, which involves identifying issues with the analysis, such as incompleteness of the data or insufficiency of the impact categories. This Section concludes with an analysis of how the results inform the research questions.

TABLE 7
LCIA Results for the ASP

Impact category	Result	Normalized
Ecosystem quality	1669.12200 PDF $\cdot$ m^2 $\cdot$ yr	0.29777
Human health	897.83083 DALY	$1.92944 \cdot 10^5$
Resources	$3.52196 \cdot 10^4$ MJ surplus energy	101.36191

TABLE 8
LCIA Results for the Locally Hosted Software

Impact category	Result	Normalized
Ecosystem quality	4238.84957 PDF $\cdot$ m^2 $\cdot$ yr	0.75621
Human health	2289.78568 DALY	$4.92075 \cdot 10^5$
Resources	$9.04187 \cdot 10^4$ MJ surplus energy	260.22515

TABLE 9
Weighting Configurations

Number	Ecosystem quality	Human health	Resources
1	1	0	0
2	0.75	0.25	0
3	0.75	0	0.25
4	0.5	0.5	0
5	0.5	0.25	0.25
6	0.5	0	0.5
7	0.25	0.75	0
8	0.25	0.5	0.25
9	0.25	0.25	0.5
10	0.25	0	0.75
11	0	1	0
12	0	0.75	0.25
13	0	0.5	0.5
14	0	0.25	0.75
15	0	0	1

4.1 LCIA Results

Tables 7 and 8 show the LCIA results for each system before weighting. The ASP has a smaller impact on all three impact categories, so regardless of the weighting configuration, it will always produce a smaller impact in a comparison between systems. However, the discrepancy between systems might grow or shrink based on the weights.

Table 9 shows the different weighting configurations employed for the study. The leftmost column assigns a number to each configuration. These numbers appear again in Tables 10 and 11 and correspond to the configurations that appear in Table 9.

Tables 10 and 11 show the results after weighting for the ASP and the locally hosted system, respectively. The rightmost column in each table shows a single score to evaluate the overall impact of the system. The range of numbers in this column shows how a weighting configuration can manipulate the outcome of an analysis.

4.2 Discussion

Table 12 shows the difference between the sums of the two systems at each weighting configuration. It presents the data sorted by the difference. The more weight assigned to HH, the greater the discrepancy. Resource use follows HH in terms of producing the largest difference. Configurations that place more weight on EQ produce the smallest differences.

Fig. 2 shows a graph of the sums for each system for every configuration. The ASP never generates a higher num-

TABLE 10
ASP Results from Various Weighting Configurations

Config.	EQ	HH	Resources	Sum
1	0.29777	0	0	0.29777
2	0.2233275	48 236	0	48 236.2233
3	0.2233275	0	25.3404775	25.563805
4	0.148885	96 472	0	96 472.14889
5	0.148885	48 236	25.3404775	48 261.48936
6	0.148885	0	50.680955	50.82984
7	0.0744425	144 708	0	144 708.0744
8	0.0744425	96 472	25.3404775	96 497.41492
9	0.0744425	48 236	50.680955	48 286.7554
10	0.0744425	0	76.0214325	76.095875
11	0	192 944	0	192 944
12	0	144 708	25.3404775	144 733.3405
13	0	96 472	50.680955	96 522.68096
14	0	48 236	76.0214325	48 312.02143
15	0	0	101.36191	101.36191

TABLE 11
Results from Various Weighting Configurations for the Locally Hosted System

Config.	EQ	HH	Resources	Sum
1	0.75621	0	0	0.75621
2	0.5671575	123 018.75	0	123 019.3172
3	0.5671575	0	65.0562875	65.623445
4	0.378105	246 037.5	0	246 037.8781
5	0.378105	123 018.75	65.0562875	123 084.1844
6	0.378105	0	130.112575	130.49068
7	0.1890525	369 056.25	0	369 056.4391
8	0.1890525	246 037.5	65.0562875	246 102.7453
9	0.1890525	123 018.75	130.112575	123 149.0516
10	0.1890525	0	195.1688625	195.357915
11	0	492 075	0	492 075
12	0	369 056.25	65.0562875	369 121.3063
13	0	246 037.5	130.112575	246 167.6126
14	0	123 018.75	195.1688625	123 213.9189
15	0	0	260.22515	260.22515

TABLE 12
Difference between the Sums of the Two Systems

Ecosystem quality	Human health	Resources	Difference
0	1	0	299 131
0	0.75	0.25	224 387.9658
0.25	0.75	0	224 348.3647
0	0.5	0.5	149 644.9316
0.25	0.5	0.25	149 605.3304
0.5	0.5	0	149 565.7292
0	0.25	0.75	74 901.89747
0.25	0.25	0.5	74 862.2962
0.5	0.25	0.25	74 822.69504
0.75	0.25	0	74 782.5267
0	0	1	158.86324
0.25	0	0.75	119.26204
0.5	0	0.5	79.66084
0.75	0	0.25	40.05964
1	0	0	0.45844

ber than the system of locally hosted software, suggesting that the ASP invariably has a smaller impact. A few of the graph's bars do not show up because of their small size. The bars that are too small to show up in the graph correspond to configurations that do not emphasize HH very much.

One interpretation of the data suggests that an environmental analysis that places little concern on HH would show little reason to pick one design over the other. The configurations with little weight for HH produce the smallest impacts. However, the differences between the sums correlate with the overall size of the effects. In other words, the increase in the difference between overall effects occurs alongside an increase in the size of the overall effect. The biggest overall effects occur when maximizing the weight on HH. Tables 10 and 11 show that HH produces larger numbers for both systems. The dominance of HH comes from the carbon dioxide, which makes up over 99% of the HH effects for both systems. These results suggest that designers should focus almost exclusively on global warming potential because the other impacts have such a relatively small effect that the weighting for human health must approach zero for them to appear significant.

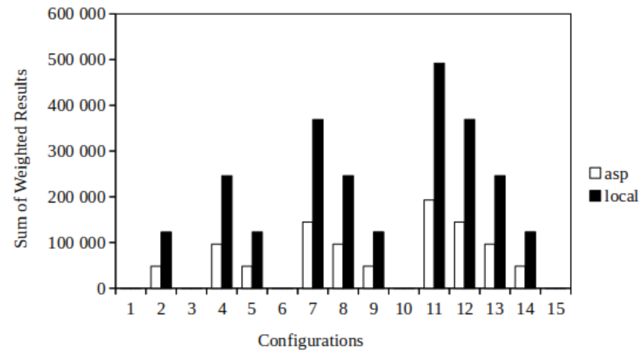

Fig. 2. The sums of each system.

Ultimately, the results do not offer a clear answer to how a weighting configuration might dictate system design. They suggest that a centralized system offers a less impactful option when compared to a decentralized system. However, this result might come from how the approximations in the study favor the centralized design. For example, the absence of networking equipment in the LCA may cause an underestimation of the ASP's impact.

The results suggest that energy use correlates with raw material use. The ASP does not have as much physical material, and it correlatingly uses less energy. Fig. 3 and Fig. 4 present a graphical comparison of the energy and mass of the two systems, showing that the two features increase together.

The paper now returns to its research questions. For the first question, the results indicate that the weighting configurations have a negligible effect on design decisions because the results uniformly favor the centralized design. If one of the configurations had produced numbers showing a smaller impact for the decentralized method, then the results would have shown the significance of weighting. This event did not occur, so nothing in the study shows that weighting configurations will affect design very much. However, the results of this study may not generalize to other systems, so the reader should not take this answer as proof that weighting does not affect design.

For the second research question, the results suggest that environmental consequences correlate. Tables 10 and 11 show that the locally hosted system has an impact at least as large as the ASP in every impact category. However, as with the answer to the first research question, the reader should take caution in generalizing this result to other systems.

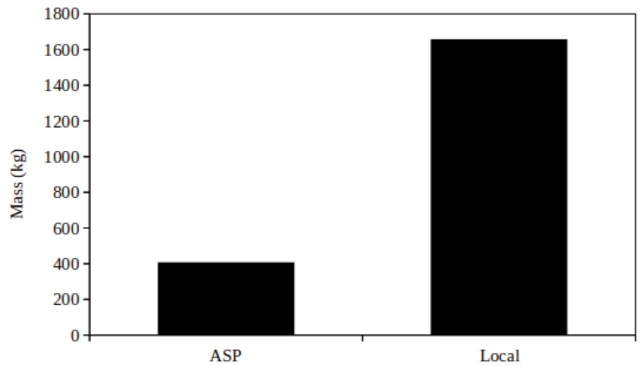

Fig. 3. The mass of each system.

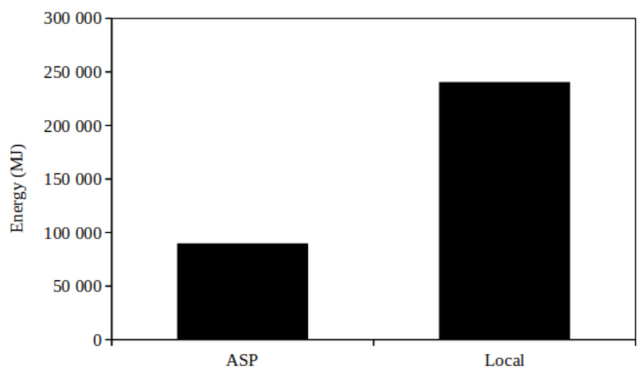

Fig. 4. The energy of each system.

5 Conclusion

The study found that the weighting did not change which of the two system designs has a smaller overall environmental impact. It also found that the different types of impacts correlate with the systems tested, making weighting negligible.

5.1 Concluding Positions

The results suggest similar conclusions as past studies, thereby confirming and strengthening their evidence. These past results concluded that server client models have a smaller environmental impact than equivalent systems that run on desktop computers. This study produces no evidence of tradeoffs for this type of system. However, these results might not generalize to centralized and decentralized systems. To illustrate this point, note that this paper focuses on centralization in a hardware sense. For software, centralized systems might not always have a smaller impact. A researcher could hypothesize that decentralized software structure allows for greater control over environmental management and thus a smaller impact.

The LCIA showed that the impact factors had a much greater effect on the results than the weighting. The only time the HH impact category did not dominate occurred when the researcher set its weight to zero. The biggest emission contribution came from carbon dioxide equivalents. This result suggested that global warming causes significantly more damage than any other environmental consequence included in the Eco-Indicator data. Because of the dominance of this impact category, weighting had a minimal effect.

5.2 Implications

The results imply that the established wisdom of green technology design is valid. Nothing in the results indicates a problem with the conclusions of past research. The issue with making tradeoffs among impacts would come from the potential of creating disastrous consequences in one category to improve the situation in another category. However, this study did not find one category improved while another deteriorated, so the examined systems do not have this tradeoff problem. The results suggest that system designers do not always have to compromise among impacts.

The results also imply that global warming is the most significant consequence with respect to these systems. Assuming the accuracy of the characterization factors in Eco-Indicator 99, the other impacts have relatively little effect. The results suggest that computer systems contribute to global warming potential more than any other category. Because of the magnitude of this category, system designers do not need to use an all-inclusive approach like the LCA to gauge the impact of their designs. A less demanding alternative that focuses exclusively on carbon emissions will suffice.

5.3 Limitations

This study had numerous limitations. Data availability severely restricted how the LCA progressed. The lack of information completely dictated both the system boundary and data requirements. The databases contained errors, and portions of their contents have aged more than ten years.

Also, the study did not account for all the hardware components. For computer monitors, this detail did not matter because both systems theoretically had the same number and type of monitors. But for network hardware, an issue arose because the ASP would need more networking material than its alternative.

Finally, the data assumed all energy came from bituminous coal in the form of electricity. This assumption about the source of electricity might reasonably approximate reality in terms of environmental impact, but the reader should remain aware of it in case it does not.

5.4 Future Research

Future research can further investigate how the methodologies behind impact assessment affect designs. Other systems, especially those that involve compromises among impact categories, would produce different results when tested with multiple weighting configurations. Other future research might entail performing LCAs on smaller products. Components from smaller product systems build up larger, complex systems in the LCA method, so having a catalogue of research on individual parts would enable researchers to conduct assessments more easily and accurately on systems composed of the smaller systems. Finally, future research can focus on how assessment methods of varying rigor differ in their results. LCA demands a lot of investment, so if it does not add much beyond what a less-rigorous method would find, engineers and analysts might benefit from knowing when it would be more than they need.

ACKNOWLEDGMENT

The authors thank Prof. Michael Hoffman and Prof. Reza Toossi of CSU Long Beach for their feedback.

REFERENCES

[1] H. Gloge, "Environmental comparison of the relevance of PC and thin client desktop equipment for the climate, 2008," Munich, Germany, 2008. [Online]. Available: www.igel.com/fileadmin/user/upload/documents/TCecology2008_en.pdf
[2] H. Gloge, "Thin clients 2011: Ecological and economical aspects of virtual desktops," Munich, Germany, 2011. [Online]. Available: www.igel.com/fileadmin/user/upload/documents/PDF_files/White_Paper_EN/thinclients2011-en.pdf
[3] *Environmental Management: Life Cycle Assessment: Principles and Framework*, International Organization for Standardization Std. 14 040, 2006. [Online]. Available: www.iso.org/iso/catalogue_detail?csnumber=37456
[4] *Environmental Management: Life Cycle Assessment: Requirements and Guidelines*, International Organization for Standardization Std. 14 044, 2006. [Online]. Available: www.iso.org/iso/catalogue_detail?csnumber=38498
[5] M. Baitz *et al.*, *GaBi Database & Modelling Principles 2016*, Leinfelden-Echterdingen, Germany, January 2016. [Online]. Available: www.gabi-software.com/uploads/media/GaBi_Modelling_Principles_2016.pdf
[6] T. Tsoutsos, N. Frantzeskaki, and V. Gekas, "Environmental impacts from the solar energy technologies," *Energy Policy*, vol. 33, no. 3, pp. 289–296, February 2005. doi: 10.1016/S0301-4215(03)00241-6
[7] L. Ramroth, "Comparison of life-cycle analyses of compact fluorescent and incandescent lamps based on rated life of compact fluorescent lamp," Rocky Mountain Institute, Basalt, CO, USA, Tech. Rep. C08-12, February 2008. [Online]. Available: c.ymcdn.com/sites/www.productstewardship.us/resource/resmgr/imported/RMI_CFLvincad.pdf
[8] D. il Ra and K.-S. Han, "Used lithium ion rechargeable battery recycling using Etoile-Rebatt technology," *Journal of Power Sources*, vol. 163, no. 1, pp. 284–288, December 2006. doi: 10.1016/j.jpowsour.2006.05.040
[9] I. Hermann and A. Moltesen, "Does it matter which Life Cycle Assessment (LCA) tool you choose? – a comparative assessment of SimaPro and GaBi," *Journal of Cleaner Production*, vol. 86, pp. 163–169, January 2015. doi: 10.1016/j.jclepro.2014.08.004
[10] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen, and E. Meijer, *Introduction to LCA with SimaPro*, Amersfoort, Netherlands, November 2013.
[11] P. Hofstetter, A. Braunschweig, T. Mettier, R. Müller-Wenk, and O. Tietje, "The mixing triangle: Correlation and graphical decision support for LCA-based comparisons," *Journal of Industrial Ecology*, vol. 3, no. 4, pp. 97–115, October 2000. doi: 10.1162/108819899569584. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1162/108819899569584/pdf
[12] *Eco-Indicator 99 Manual for Designers: A Damage Oriented Method for Life Cycle Impact Assessment*, The Hague, Netherlands, 2000. [Online]. Available: www.pre-sustainability.com/download/EI99_Manual.pdf
[13] [Online]. Available: www.openlca.org
[14] D. Maga, M. Hiebel, and C. Knermann, "Comparison of two ICT solutions: Desktop PC versus thin client computing," *The International Journal of Life Cycle Assessment*, vol. 18, no. 4, pp. 861–871, May 2013. doi: 10.1007/s11367-012-0499-3. [Online]. Available: http://link.springer.com/content/pdf/10.1007%2Fs11367-012-0499-3.pdf
[15] "Resolution adopted by the General Assembly," 2005. [Online]. Available: data.unaids.org/Topics/UniversalAccess/worldsummitoutcome_resolution_24oct2005_en.pdf
[16] H. S. Matthews, C. T. Hendrickson, and D. H. Matthews, *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter*. LCAtextbook.com, 2015. [Online]. Available: www.lcatextbook.com
[17] A. K. Jönbrink, "Lot 3 personal computers (desktops and laptops) and computer monitors," Gothenburg, Sweden, 2007. [Online]. Available: extra.ivf.se/ecocomputer/downloads/Eup\%20Lot\%203\%20Final\%20Report\%20070913\%20published.pdf
[18] J. B. Guinée *et al.*, *Handbook on Life Cycle Assessment*. New York, NY, USA: Kluwer Academic Publishers, 2004.
[19] *Personal Computer Configuration and Management Standard*, EPA Information Standards Std. CIO 2122-S-02.0, 2005. [Online]. Available: www.epa.gov/sites/production/files/2013-11/documents/percom.pdf
[20] "Hosted EHR vs. server based," Phoenix, AZ. [Online]. Available: www.mdsmedicalsoftware.com/resources/hosted-ehr-vs-onsite-server/
[21] "What are the disadvantages and advantages of asp vs. locally hosted?" Rockville, MD. [Online]. Available: www.hrsa.gov/healthit/toolbox/RuralHealthITtoolbox/Selection/aspvslocallyhosted.html
[22] *U.S. LCI Database Project: User's Guide*, Golden, CO, 2004. [Online]. Available: www.nrel.gov/lci/pdfs/users_guide.pdf
[23] R. Kemma, M. van Elburg, W. Li, and R. van Holsteijn, *MEEUP Methodology Report*, Delft, Netherlands, November 2005. [Online]. Available: www.vhknet.com/download/MEEUP_Methodology_fin.pdf
[24] M. Goedkoop and R. Spriensma, *The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment*, Amersfoort, Netherlands, 2001. [Online]. Available: www.pre-sustainability.com/download/EI99_annexe_v3.pdf
[25] P. Hofstetter, *Perspectives in Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valueshpere*. New York, NY, USA: Springer US, 1998.
[26] R. S. J. Tol, "Estimates of the damage costs of climate change part 1: Benchmark estimates," *Environmental and Resource Economics*, vol. 21, no. 1, pp. 47–73, January 2002. doi: 10.1023/A:1014500930521
[27] R. S. J. Tol, "Estimates of the damage costs of climate change part 2: Dynamic estimates," *Environmental and Resource Economics*, vol. 21, no. 2, pp. 135–160, February 2002. doi: 10.1023/A:1014539414591
[28] M. Z. Hauschild and H. Wenzel, *Environmental Assessment of Products Volume 2: Scientific Background*. New York, NY, USA: Springer US, 1998.
[29] T. Vermeire *et al.*, "European Union system for the evaluation of substances (EUSES). principles and structure," *Chemosphere*, vol. 34, no. 8, pp. 1823–1836, April 1997. doi: 10.1016/S0045-6535(97)00017-9
[30] T. Blonk, R. Spriensma, M. Goedkoop, A. A. B. van Engelenburg, and K. Blok, *Drie Referentieniveau's voor Normalisatie in LCA [Three Reference Levels for Normalization in LCA]*. Lelystad, Netherlands: RIZA, 1997.

Bertrand Ithurburn (M'15) received the BS degree in computer science and engineering from the University of California, Davis, CA, USA in 2014 and the MS degree in computer science from California State University, Long Beach, CA, USA in 2016. He is graduate student at the Graduate Center at City University of New York, NY, USA.

Birgit Penzenstadler (M) received the PhD degree from the Technical University of Munich, Germany in 2011.

She is an Assistant Professor of software engineering at California State University, Long Beach. Her research focuses on software engineering for sustainability and resilience, and she leads the Resilience Lab at CSULB.