Weighting Environmental Impacts in Software Distribution Systems

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Abstract—Developers and analysts who try to create sustainable systems may have to compromise when it comes to different environmental impacts. A nontrivial number of products saves energy, but in exchange produces dangerous material that the enery-inefficient alternative does 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, the weights have the potential to direct the green design toward neglecting lowly weighted environmental concerns. This study aims to clarify the effects of different weighting configurations. The project employs Hofstetter's mixing triangle that 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

Protecting the environment has become a concern for product designers [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], and these different types of damage do not easily compare. This situation would not present a problem if designers could reduce particular impacts without increasing others, but many products designed to minimize impacts in one domain increase their impact in another one. 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 the 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 but not on dangerous material. 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. This paper revolves around the issue of designers using environmental metrics in a way that neglects certain effects. Therefore, the 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 any specific type of software, but a process described by the International Organization for Standardization (ISO) [3] [4]. Analysts use GaBi and SimaPro more frequentl than any other software implementations of LCA. 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]. More specifically, LCA has an optional phase called the Life-Cycle Impact Assessment (LCIA), which provides ad-

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ditional information for the interpretation of LCA results [4]. Eco-Indicator 99 offers one possible way among others to implement the LCIA phase. In this paper, LCIA refers to using Eco-Indicator 99 to normalize the data and using the weighting triangle to weight the normalized data.

Due to financial constraints, this paper cannot emply SimaPro directly. Instead, it uses the normalization and weighting elements of SimaPro, Eco-Indicator 99 and the weighting triangle, with OpenLCA, a free software implementation of LCA [13]. It includes Eco-Indicator 99's normalization factors. The authors perform the weighting without the assistance of software.

To summarize, this paper examines how metrics for environmental damage account for the different types of damage. 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. Why do the different impacts do correlate? Knowing the characteristics that make products vulnerable to conflict between impacts could help future products avoid tradeoffs.

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.

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, 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. As shown by T. Tsoutsos, N. Frantzeskaki, and V. Gekas in the article "Environmental impacts from solar energy technologies," by L. Ramroth in the article "Comparison of life-cycle analyses of compact fluorescent and incandescent lamps based on rated life of compact fluorescent lamp," and by D.-i. Ra and K.-S. Han in the article "Used lithium ion rechargeable battery recycling using Etoile-Rebatt technology," 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 compared 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. 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 components.

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 such as 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 may define the use of cooling water outside of its scope. A cooling system may 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 processes as possible.

Environmental analysis always has value judgments. Concern for the environment implies valuing it. Assessing environmental impact entails other value judgments, such as how much value to place on human wellbeing in relation to ecological preservation. 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]. Researchers using certain techniques to analyze environmental impacts take data from studies that analyzed impacts using different methods. 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]. Researchers often cannot use direct measurements. Consequently, when a paper uses primary information, those data then show up in subsequent studies [14] [1]. Researchers should only go to secondary sources if they must. 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 the inferior data sources.

Given that many of the studies use similar, occasionally identical, data, it comes as no surprise that they 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. One study that uses a full LCA finds the same advantages for client server systems [14]. This study found lower quantities of physical material and energy for the thin client system. Other researchers have tested multiple 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 do so 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. Other 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, including both cradle-to-gate and cradle-to-grave LCAs.

Furthermore, studies occasionally neglect to account for energy production [14] [2] [17]. The quantity of energy used might appear, but the impact of producing the energy does not always enter into the analysis. As such, these studies do not specify from where the energy comes. 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, so it 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 proper 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. Not every practitioner has access to LCA experts, whom the LCA guidelines recommend be consulted [4]. The level of rigor involved in a complete LCA undermines its practicality.

2.3 Identified Research Gap

The need for research in this field comes from how environmental concerns can dictate system design. 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 becomes relevant.

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.

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. Requirements engineers can use this information to design sustainable systems. The LCA focuses on these three impact categories:

human health, resource use, and ecosystem quality. Eco-Indicator 99, which the assessment phase of this LCA employs, has 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. As such, the goal does not constitute a comparative assertion disclosed to the public as defined in the LCA standards [18].

This study uses LCA instead of alternatives such as Design for the Environment or the GREET Model because existing research tools for environmental weighting configurations, including the mixing triangle, use LCA as a foundation [11]. This particular LCA acts as part of a larger research paper that will use this triangle. Therefore, LCA serves as an appropriate tool for this particular study.

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 decided this range. Data collection took place over a six month period from 2015 into 2016. However, the researcher 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 come from reports that use a technique called a Methodology for Eco-design of Energy-Using Products (MEEUP) to analyze hardware products. These analyses use data that range from ten to five years in age [2] [17]. The collection and writing of the LCA occurred over the course of an academic year, and 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 do not exist in the proper form for LCA or cost too much for the researcher 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 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 researcher has 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 purpose is to illustrate how environmental considerations affect system design.

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 assessment does not consider every possible systems. 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

TABLE 1
The Inputs and Outputs of the MEEUPs

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

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

these exclusions, the assessment fails to account for any advantages SaaS or an intermediate option might offer.

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 enters or leaves the systems and any substance or energy that comes from or enters the environment. These substances and energies enter and leave without previous human transformation.

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. Similar to 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 to document its inputs and emissions.

3.2.3 Types and Sources of Data

This LCA does not have primary data. The 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].

The MEEUP results in the two papers track these three types of inputs for most processes, including energy, process water, and cooling water. For general waste, the analysis divides 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. 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 the particular substances causing the acidification potential to increase, so the LCA assumes sulfur dioxide causes all of the acidification potential. For each category, the LCA uses the closest approximation available in the database.

Table 2 also classifies each entry by its flow type. 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.

3.3 Relating Data to the Functional Unit

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 single thin client or desktop computer for nine hours a day [14]. Based on the same research, a year has 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 or completely shut down. For thin clients, softoff machines generally still consume power in practice. 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

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

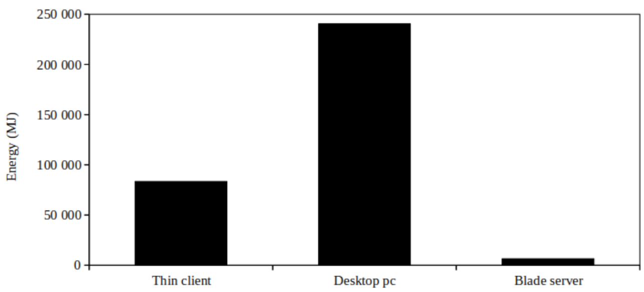

Fig. 1. Total energy use of each machine over a five year period.

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.

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.

3.4 Life Cycle Impact Assessment (LCIA)

After acquiring and processing the data, LCAs next have a life cycle impact assessment (LCIA). For this particular study, the LCIA uses a method called Eco-Indicator 99. Eco-Indicator 99 has three impact categories: human health, ecosystem quality, and resource use [12]. Each impact category has its own subcategories. For human health, the subcategories include climate change, ozone layer depletion, carcinogenic effects, respiratory effects, and ionizing radiation. For ecosystem quality, the subcategories include ecotoxicity, acidification, eutrophication, and land use. For resources, 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 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. This LCA will use the individualist perspective because it has a shorter time perspective than the other two options, the hierarchist and egalitarian perspectives. 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 buy the individualist perspective.

Each impact category has a characterization model. The individualist characterization model for human health uses concentrations from emission flows over a period of 100 to 200 years [24]. 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. The climate change model derives its estimates from General Circulation Models based scenarios documented in R. 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 human health subcategory concern 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 models 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 model addresses acidification and eutrophication. This latter model 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 affects human health, so carbon dioxide becomes relevant to the climate change subcategory and its containing human health impact category. Every relevant flow has a characterization factor assigned to it based on the size of its impact. Carbon dioxide

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	$6.0 \cdot 10^{-7} \frac{\text{DALY}}{\text{kg}}$

has a characterization factor of 0.013333 $\frac{\text{DALY}}{\text{kg}}$. These characterization factor numbers come from the characterization models for each impact category. The researcher multiplies 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 researcher has to enter every individual flow into Eco-Indicator from NREL's database, but the large quantity of flows makes 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, as well as the elementary flow for the bituminous coal. For the sake of space, the table uses the synonymous phrase "impact factor" in place of "characterization factor" in the table's header. The researcher fabricated the value for the coal 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 the default Eco-Indicator data.

3.5 Normalization

The OpenLCA implementation of Eco-Indicator 99 has 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 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 symbol 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 normalization factors come directly from the OpenLCA LCIA database, so this study uses the same number of significant figures as the database.

TABLE 6
Normalization Factors for Each Impact Category

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

TABLE 7
LCIA Results for the ASP

Impact category	Result	Normalized
Ecosystem quality	$1669.12200 \text{ PDF} \cdot \text{m}^2 \cdot \text{yr}$	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	$4238.84957 \text{ PDF} \cdot \text{m}^2 \cdot \text{yr}$	0.75621
Human health	2289.78568 DALY	$4.92075 \cdot 10^5$
Resources	$9.04187 \cdot 10^4$ MJ surplus energy	260.22515

3.6 Weighting

This LCA uses multiple weighting configurations. The configurations compromise between human health, ecosystem quality, and resource use. The three weighting factors, one for each impact category, must add up to 100%. The researcher multiplies the factors by the corresponding numbers that represent the impact for one of the categories. This LCA uses a mixing triangle with the same impact categories as Eco-Indicator 99, although researchers could theoretically formulate different categories for weighting [11].

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 finishes with analyzing how the results inform the research questions.

4.1 LCIA Results

Tables 7 and 8 show the LCIA results for each system without weighting. The ASP has a smaller impact on all three impact categories, so regardless of the weighting configuration, it will always produce the preferable results 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 in Tables 10 and 11 and corresponds to the configurations that appear in Table 9.

Tables 10 and 11 shows the results after weighting for the ASP and the locally hosted system, respectively. The rightmost column 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.

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

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

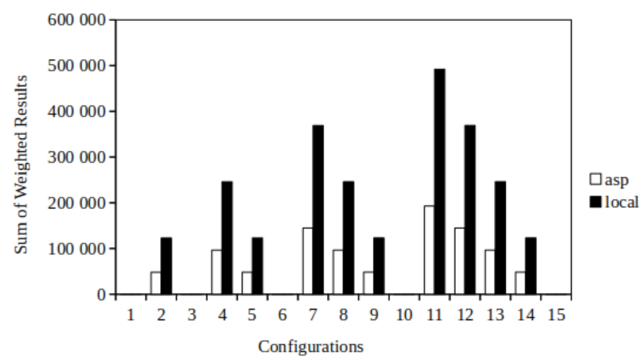

Fig. 2. The sums of each system.

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 human health, the greater the discrepancy. Resource use follows human health in terms of producing the largest difference, and configurations that place more weight on ecosystem quality produce the smallest differences.

Fig. 2 shows a graph of the sums for each system for every configuration. The ASP never generates a higher number, 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 come from configurations that do not emphasize human health.

One interpretation of the data suggests that an environmental analysis that places little concern on human health would show little reason to pick one design over the other. 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 reflects an increase in the size of the overall effect. Tables 10 and 11 show that human health produces larger numbers for both systems. The dominance of human health comes from the carbon dioxide, which makes up over 99% of the human health effects for both systems. These results suggest that designers should focus almost exclusively on global warming potential because the other impacts have such a small effect unless the weighting for human health approaches zero.

Ultimately, the results do not offer a clear answer to how a weighting configuration might dictate system design. They suggest that a centralized system offer a superior option to a decentralized system. However, the approximations on the systems favor the centralized design. The absence of networking equipment in the LCA may cause an underestimation of the ASP's impact. Also, the results suggest that energy use correlates with raw material use.

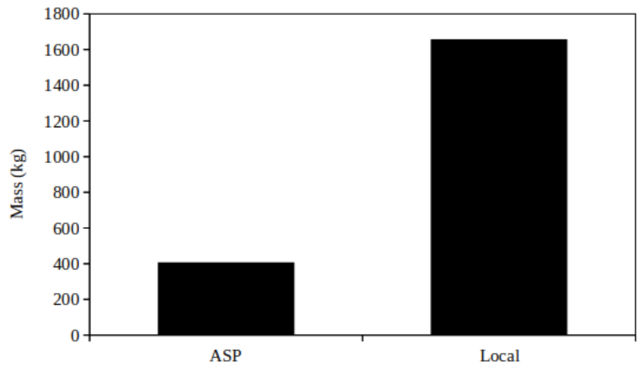

Fig. 3. The mass of each system.

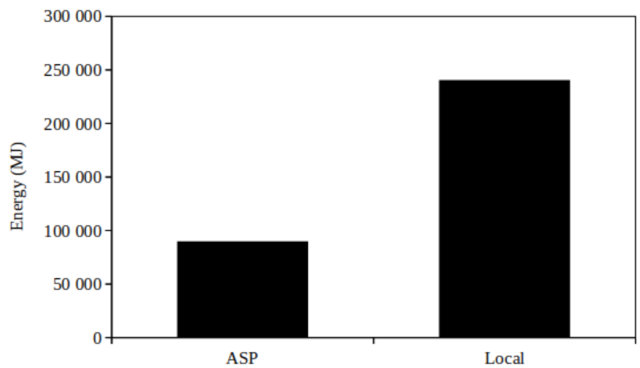

Fig. 4. The energy of each system.

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. The two features correlate. The system with more mass uses more energy present a graphical comparison of the energy and mass of the two systems. The two features correlate. The system with more mass uses more energy.

For the first research question, the results indicate that the weighting configurations have a negligible effect on design decisions because the results uniformly favor the centralized deign. 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.

4.3 Analytical Investigation

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. This paper focuses on centralization in a hardware sense. For software, centralized systems might not always have a smaller impact. For example, the operating systems that manage servers often have decentralized structures, and this study found lower impacts with server-based systems.

The impact factors had a much greater effect on the results than the weighting. The only time the human health impact category did not dominate occurred when the researcher set its weight to zero. The biggest emission contribution comes from carbon dioxide equivalents. This result suggests 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 has 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 comes from the potential of creating disastrous consequences in one category to improve the situation in another. However, the lack of tradeoffs found in this study immunizes the examined systems to this problem. 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 such as 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 has numerous limitations. Data availability severely restricts how the LCA progresses. The lack of information completely dictates both the system boundary and data requirements. The databases contain errors, and portions of their contents comes from over a decade ago. The study does not account for all the hardware components. For computer monitors, this detail does not matter because both systems theoretically have the same number and type of monitors. But for network hardware, an issue arises because the ASP needs more networking material than its alternative. Finally, the data assume all energy comes from bituminous coal in the form of electricity.

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. Finally, future research can focus on how less demanding assessment methods differ in their results from their more expansive counterparts. LCA demands rigor, so if it does not add much beyond what a less-rigorous method would find, engineers and analysts might know when to avoid it.

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