Comparative Life Cycle Impact Assessment of Digital and Physical Distribution of Video Games in the United States

Comparative Life Cycle Impact Assessment of Digital and Physical Distribution of Video Games in the United States

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Abstract

This study examines and compares the environmental footprint of video game distribution on last generation consoles, current generation consoles and personal computers (PC). Two different methods of delivery are compared on each platform: traditional retail on optical discs and digital downloads in the U.S. Downloading content has been growing and is used to distribute movies, music, books and video games. This technology may change the environmental footprint of entertainment media. Previous studies on books, music, movies and television shows found that digital methods of distribution reduced emissions. However, prior research on video games, looking only at previous generation consoles, found the opposite conclusion.

In this thesis, life cycle assessment (LCA) is used to measure all background and foreground emissions with the U.S. EPA's TRACI 2.1 framework. Data is gathered through a combination of previous work and experimental power consumption data gathering. Results are also tested with four different sensitivity analyses. I found that digital distribution resulted in lower emissions for last generation consoles across all TRACI 2.1 impact categories, but were mixed on current generation consoles and PC. Once results were normalized, digital distribution had higher emissions for the TRACI 2.1 categories with significant impact factors than their physical counterparts. Sensitivity analysis indicated that increasing energy efficiency of data transfer over time and smaller file sizes prevalent in downloads generated emissions below or comparable to the

physical cases. Normalized sensitivity cases demonstrated this to also be true for the TRACI 2.1 impact categories with the highest impact factors.

Further research into internet infrastructure, manufacturing practices for physical media, and consumer behavior may help to better clarify the potential impacts of downloading and streaming as they continue to grow in predominance and user share as a method of entertainment media distribution.

Author's Biographical Sketch

A gamer since a young age, Cathryn E. Buonocore came to Harvard Extension School after getting interested in environmental and health issues during a term of AmeriCorps service with Pioneer Valley Habitat for Humanity in Northampton, Massachusetts. Habitat for Humanity International had been introducing health and environmental issues into its building standards, which had been heavily adopted by the Pioneer Valley affiliate, and she became immersed in these issues. After coming to Harvard Extension School's Sustainability and Environmental Management (SEM) program, she saw how applicable concern for the environment could be to anything. While working at the Harvard T.H. Chan School of Public Health's Center for Health and the Global Environment, she met Dr. Greg Norris and learned about his handprinting methodology and life cycle assessment (LCA), further reinforcing the applicability of sustainability and how easy reducing emissions and making positive impacts could be. While considering potential thesis topics for the SEM program, she took his life cycle assessment class, which featured a final project of comparing how a student currently does something in their life, finding a new way to do it and see if it results in lower emissions or a positive impact using LCA. Cathryn had an existing interest in video games and technology in general, and piloted the idea of purchasing video games on her Playstation 3 digitally instead of physically. As the results were positive, that research was expanded out to become this thesis.

Dedication

Dedicated to the memories of Shirley E. Reynolds Tibbitts and Ona A. Dietrich Buonocore, my grandmothers, who both passed away in October 2015 while this work was in progress.

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I would like to first thank my research advisor Dr. Mark Leighton for his guidance and patience on developing the topic and helping me navigate the thesis process, and for his openness and curiosity about my ideas as they developed.

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I thank my thesis advisor Dr. Greg Norris, for introducing me to life cycle assessment and his handprinting methodology, giving me the chance to pilot this idea in his Fall 2014 E-151 class, and then helping me turn that pilot project into this thesis.

Lastly, I want to thank for closest friends and family for the ups and downs during this entire process. I especially want to thank my late grandmothers, who both died in the early phases of this work, and whom I miss dearly.

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Chapter I

Introduction

Humans have sought entertainment throughout our history. In contemporary times, people have access to forms of entertainment ranging from professional Broadway productions to local play groups, movies and television on demand, amateur videos on YouTube, music on vinyl records, compact discs (CDs), or from internet streams and downloads, and relatively recently, video games.

Changes in technology and tastes have driven changes in entertainment as well as how it is accessed. Like other human activities, accessing and consuming entertainment has an environmental impact that can be measured. Digital methods of distributing entertainment are a recent technological advancement. It gives consumers another choice and more power over their entertainment access, and possibly a way to reduce their environmental footprint.

Research Significance and Goals

This study aims to look at video games, and how downloading games compares to distribution of physical discs via retail, using life cycle assessment (LCA) methodology. This method measures the environmental impacts of a product or service. LCA follows a product's life from beginning to end to measure its contribution to environmental impacts traceable to its creation, use and disposal. It can also focus on a specific stage or stages.

The disposal stage is commonly referred to as the "end-of-life" (EOL). LCA can measure many different emissions created from a product's life cycle, such as carbon dioxide and carcinogens, and resources used during its life, such as fossil fuels (Baumann & Tillman, 2004).

But why do games matter, both for society and potentially environmentally? Today, the video games industry is one of the fastest growing sectors within the economy. In 2013, the industry as a whole reported $21 billion in revenue in the United States alone, with $93 billion worldwide. This growth is expected to continue, with projections that the industry will generate $111.1 billion in revenue worldwide in 2015 (Games: Improving the Economy, 2014).

American households have an average of two gamers, and155 million Americans play video games in some form.. Forty-two percent of Americans play video games regularly, measured as active play for at least three hours per week. Four out of five American households have a device that is used to play video games. Fifty-one percent of households have a device devoted entirely to gaming. Gamers include people across all age and gender lines, with the statistically average gamer being a 35-year-old male. More women over the age of 18 play games than boys under 18 (2015 Sales, Demographic and Usage Data: Essential Facts about the Computer and Video Game Industry, 2015).

Digital downloads sold more than physical retail releases for the first year in 2013. This includes additional downloadable content (DLC) for games on consoles and PC. It also includes sales on mobile platforms such as Android phones and iPhones, where downloading is the only way to access games (Games: Improving the Economy,

2014). From 2010 to 2014, digital sales grew from 29% to 52% of the total market sales. This figure includes social network games such as those on Facebook, subscription-based games, add-on content and mobile apps (Sales, Demographic and Usage Data, 2015). Digital downloads are often praised for their convenience to the consumer, regardless of platform, and are recognized as the way gaming is heading (Tipps, 2014).

Background

Moving towards sustainability necessitates reducing the environmental and health footprints of the products that we use. Goods that we make have a variety of effects on human health and the environment.

Environmental and Health Issues and Impacts

The environmental emissions and pollution generated from various industrial and consumer processes can have many effects on the environment and subsequently, human and ecological health. Carbon dioxide, released from the burning of fossil fuels, has been implicated as a primary culprit behind climate change. The effects of climate change range from the melting of polar ice caps in the Arctic, to more frequent, stronger tropical storms. Some areas, such as the western United States and Australia, may experience more frequent and extreme droughts due to less rain, or less reliable winter snowfall creating spring meltwater to begin the growing season. Others, like the eastern United States and some areas of South America, may see more frequent extreme rains and floods (International Panel on Climate Change, 2015).

Temperatures around the world may shift. Places like the United Kingdom may become warmer, while a handful of places may become cooler or see more extreme cool temperatures and blizzards. This may cause wildlife to change its distribution with some species dying off if they cannot adapt to a new climate and ecosystem. Oceanic ecosystems may degrade due to warmer waters and acidification, which may kill off shellfish and cause coral bleaching events. Like terrestrial animals, sea life may shift ranges as habitats become unsuitable (International Panel on Climate Change, 2014).

Droughts and floods could affect worldwide food markets, causing price instability for staple foods, or local and regional famines. Infectious diseases may be able to take hold in areas that were originally an unsuitable climate for a pathogen itself or its vector. This would allow such a disease to infect new populations and spread. Increasing temperatures could lead to positive feedback loops – melting Arctic permafrost can release trapped methane, another known greenhouse gas, and further reinforce the warming cycle. More extreme temperatures may cause people to use more electricity to power heating and cooling systems, releasing more greenhouse gases from fossil fuels. More frequent extreme weather events may devastate communities, killing people directly and in their aftermath. Coastal cities in particular will have to adapt to rising sea levels (International Panel on Climate Change, 2015).

Industrial processes have environmental implications besides climate change. The release of nitrous oxides (NO_x) and volatile organic compounds (VOCs) at the ground level leads to chemical reactions that form ozone (smog) in some atmospheric conditions. This reaction typically occurs on hot sunny days, when solar energy fuels the reaction. Inhaling ground level smog can make people sick as well as aggravate those

with existing respiratory illnesses. Children are at most risk from exposure to ground level smog (Environmental Protection Agency, 2015, October).

There are other health concerns. Fine particulate matter 2.5 (PM 2.5) is tiny particulates less than 2.5 microns in diameter. These particles, when inhaled, are capable of penetrating into the deepest part of the lungs, bypassing defensive measures. As these particulates accumulate over time, they can cause a variety of respiratory and cardiopulmonary ailments such as lung cancer. Fine particulates are also asthma triggers (World Health Organization Regional Office for Europe, 2013).

Industrial activities also emit pollutants that deplete the stratosphere's ozone layer. Primary among those emissions are chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). These chemicals are also potent greenhouse gases. The ozone layer helps to keep out harmful radiation from the sun, such as ultraviolet (UV) radiation. The layer's breakdown due to environmental emissions allows more UV radiation to reach the surface. This increase in surface UV radiation has been implicated as a cause of rising rates of skin cancers such as squamous cell carcinoma, basal cell carcinoma, and the highly malignant melanoma. In addition to skin cancer, UV radiation is also thought to be contributing to eye problems such as cataracts and inflammation (United Nations Environmental Programme, 2006).

Pollution is also detrimental to land and water. Farming in particular is cited as a major cause of eutrophication of water bodies. Farms use high quantities of synthetic fertilizers which are rich in nitrogen and phosphorus. Rainfall causes excess fertilizer to run off fields into nearby water, where they are carried downstream and eventually into the ocean. Where these compounds collect, algae rapidly over grows, consuming

nutrients in the water. The overgrowth depletes oxygen, and changes the overall composition of the ecosystem as other life can be completely choked off. Eutrophication can also encourage the growth of algae that are directly toxic to humans and wildlife, damaging recreational waters (Environmental Protection Agency, February 2015).

The impacts of human activity also extend directly to health, with various pollutants causing many health effects. Among the most common are VOCs, which are carbon containing compounds that easily turn into vapor. Benzene is one such compound, and is a byproduct of the combustion of fossil fuels. It is linked to numerous health problems for both acute and long-term exposure. Acute inhalation causes mucus membrane irritation, dizziness, headache, and if exposure lasts long enough, loss of consciousness. Long-term exposure is linked to anemia, reproductive effects for women, and adverse effects on fetuses. Increased risk of leukemia has also been documented for people exposed occupationally. Benzene is also present in tobacco smoke (Environmental Protection Agency, 2015, September). Other effects of VOC exposure range from allergy and asthma irritation to skin reactions. Some VOCs besides benzene, such as formaldehyde, are known carcinogens. Some VOCs have no known effects (National Library of Medicine, 2015).

These are just some of the environmental and health effects that pollution and emissions from human activities can have. Pollution reduction could decrease both environmental and health impacts from industrial and consumer processes.

Video Games Then and Now

Video games, since their inception, have gone through many changes, both in and of themselves and in the technology, culture, and economy surrounding them. Understanding their history as a form of entertainment can aid in understanding how they have become what they are today, and why their distribution is a question worth considering from an LCA standpoint.

Video games began with the first generation in the 1970s with Pong consoles and the Magnavox Odyssey. During the 1980s and the second generation of gaming, cartridges were developed for use with the Fairchild Channel F. Atari also came out with the Atari 2600 console that used cartridges and brought them into the mainstream consumer market. The introduction of the Commodore 64 made computer gaming a viable alternative to console gaming during this time. In the late 1980s, during the third generation of gaming, Nintendo came out with the Nintendo Entertainment System (NES) and its iconic character, Mario. During the early 1990s with the fourth generation, Nintendo came out with its Super Nintendo (SNES) console, which competed with the Sega Genesis and its counterpart to Mario, Sonic the Hedgehog. IBM's DOS-based personal computers (PCs) and their games were also becoming common in households (Generations of video games, 2014).

During the fifth generation in the mid 1990s, Sony entered the console market with the Playstation, which competed with the Nintendo 64 and Sega Dreamcast. This generation marked when optical discs began to replace cartridges as the preferred medium of delivering games. The Dreamcast and Playstation both used optical discs instead of cartridges, while the Nintendo 64 stuck with cartridges. In the late 1990s and

early 2000s, the sixth generation of gaming hardware come out. Sega dropped out of the console race, and Microsoft took its place by releasing the Xbox. Sony released the Playstation 2 and Nintendo had the Gamecube. All three of these consoles used discs, making cartridges an obsolete technology. Online gaming also started its rise (Generations of video games, 2014). Valve Corporation launched its Steam platform for PC gaming during the sixth generation, in 2003, which first made games legally available as digital downloads (Plunkett, 2013). In the mid 2000s, the seventh generation, began. There was Sony's Playstation 3, Microsoft's Xbox 360, and Nintendo's Wii. These consoles and their games are still easy to obtain at large retailers. During this time, online gaming also became standard (Generations of video games, 2014).

At the present time, gaming is in the eighth generation, with the Playstation 4 (PS4), Xbox One and Nintendo WiiU (Games: Improving the Economy, 2014). Steam remains very popular for PC gaming, with 125 million active accounts as of February 2015 (Plunkett, 2015). As a result, it is possible to buy video games in different ways. Physical copies of games on discs can still be bought at retailers, such as GameStop, Target, Wal-Mart and Best Buy. They can also be ordered from online retailers like Amazon. But in the internet age, most games can also be purchased and downloaded from services such as Steam, Playstation Network, Nintendo eShop and Xbox Live Arcade (XBLA) (Kotaku Staff, 2012).

PC Gaming and Digital Sales

Ever since digital distribution technology was introduced to the gaming industry with the launch of Steam on PC in 2003 (Plunkett, 2013), it has been growing its market

share as shown above. Digital downloads are popular for PC gaming and the dominant form of distribution in that market; in 2013, 92% of PC games were sold digitally (Sacco, 2014). Steam is known within the gaming community for holding regular, constant sales, with large sale events occurring at certain points during the year. It also boasts a large user base of 125 million active accounts (Plunkett, 2015). However, it is worth noting that Valve never forces publishers and developers to put their games on sale for low prices. Cheap prices on Steam is a major reason that the service is very popular among the PC gaming audience (Campbell, 2014).

An example of Steam's sale pricing in practice is *The Elder Scrolls V: Skyrim* from Bethesda Software. *Skyrim*, released in 2011, is arguably one of the most content-rich gaming experiences to come out in the last generation. Even four years after its release, it remained one of the top-sellers of 2015, at number 10 (Sales, Demographic and Usage Data, 2015). The normal asking price on Steam for the *Skyrim Legendary Edition*, which includes the base game, the three expansion packs *Dawnguard*, *Dragonborn* and *Hearthfire*, and Bethesda's modding tool the *Creation Kit* is $39 as of April 30, 2016 (The Elder Scrolls V: Skyrim - Legendary Edition, 2016). When Steam puts it on sale, this package is discounted at rates ranging from 33% to 66% off, bringing the price down to anywhere from $14 to $27 (DeLoss, 2015). These deep discounts can be extremely enticing to consumers and save them money, particularly for people who buy a lot of games. For games such as *Skyrim*, it also provides a great deal of dollar-to-gameplay-hour value.

Among other features that make Steam appealing to consumers is social network characteristics, voice chat, the ability to join friends' games, gifting games to friends, an

extensive catalog featuring the biggest budget titles to the smallest independent (indie) games, easy user-made mod distribution and many other features (Henry, 2014). In the summer of 2015, Steam introduced a refund policy for newly bought games, provided the consumer meets two basic requirements: the game has been purchased within 14 days of the attempted refund, and has been played for 2 hours or less. If these are met, a consumer's money is returned with no further questions (Steam Refunds, 2015).

PC gamers also have other digital storefronts such as GoodOldGames (GOG.com), GreenManGaming, and Humble Bundle (Henry, 2014). One of the biggest publishers, Electronic Arts (EA) also has their own exclusive PC platform called Origin. This platform is primarily for selling EA's published titles and franchises, such as *The Sims*, *SimCity*, and *Battlefield* to PC players (About Origin, 2015). Like Steam, Origin also provides a generous refund policy, allowing consumers to refund games under a set of conditions. Gamers can refund Origin purchases within 24 hours of first launch or within 7 days from date of purchase (Great Game Guarantee, 2015).

Other publishers have their own digital platforms for their games. Among the two most notable are Ubisoft, with popular franchises such as *Assassin's Creed* and *Far Cry*, and games in the Tom Clancy franchise. Their platform is UPlay, but they also sell many games through Steam, with a link to UPlay via activation codes (UPlay Shop, 2016). Blizzard also distributes and runs its own PC games such as *World of Warcraft, Starcraft* and most recently *Overwatch* through its client, Battle.net (Battle.net Shop, 2016).

The variety of digital marketplaces creates diversity and competition for PC gamers, driving a more consumer-friendly and appealing digital shopping experience. PC gamers generally report high levels of satisfaction with their digital storefront

experience compared to console gamers (Tipps, 2014). Considering these factors, downloading is an attractive alternative to retail for purchasing games for many PC consumers, contributing to downloads as the dominant form of sale on PC.

Console Gaming and Digital Sales

On consoles, digital downloads have not caught on as much, despite all the major console manufacturers now providing digital stores and online accounts. Digital console purchases make up less than 20% of the total console purchase market, with digital buyers often still purchasing a physical copy. Retail dominating over digital sales in the console market may be due to a number of factors, such as gamers wanting a sense of ownership, resale value, conserving limited hard drive space on consoles and fears of support servers for digital purchases going offline (The democracy of downloading: What gamers expect (and want) from digital distribution, 2014).

Digital console games often take longer to start falling in price compared to their physical equivalents. This is in great contrast to PC games, which often see digital price drops and sales quickly. Due to a used game market and retail price drops after launch, physical console games often become cheaper than their digital versions quickly, making them appealing to consumers. The convenience offered by digital purchasing is not enough to offset these issues and concerns for many console players (The democracy of downloading, 2014). However, as previously stated, digital sales are growing in the industry overall and this may change on consoles in the future.

Most console gamers also acknowledge that digital is likely the way of the future, considering both digital purchase's success on PC and how digital distribution has been

adopted by other entertainment media. Many gamers think the infrastructure just may not be there yet on consoles. Consumers also report wanting streaming services, similar to Netflix, on consoles, as well as options to sell or refund old or unwanted digital purchases like on many PC digital stores (The democracy of downloading, 2014).

Other Forms of Entertainment, Digital Distribution and LCA

Some forms of media have been subjected to life cycle assessment studies to quantify environmental impacts of old and new ways of distribution. One example is music. A study published in 2010 compared the carbon dioxide emissions of a CD and a download on the iTunes music store. Emissions for the digital download were anywhere from 40% to 80% less than the impacts associated with producing and distributing the CD (Weber, Koomey & Matthews, 2010).

Another example is books, with the advent of eReaders such as Amazon's Kindle line of products. A study conducted at the Rochester Institute of Technology did a comparative LCA between a traditional bound book, an eReader model called the RED 1100 from the early 2000s, and a modern Amazon Kindle. The results, based on assumed consumer behavior of reading 60 books a year, measured three different impact areas: global warming potential, ozone depletion and acidification. The Kindle had the lowest environmental impact per book for two of the three impact areas, performing worst only in ozone depletion due to the manufacture of the device itself. A Kindle holding 8-23 books offset the emissions for global warming and acidification generated from its manufacture, by preventing the manufacture and shipping of paper books. The printed

book performed the worst given the assumed behavior, driven by energy consumption in manufacturing and fuel use in transportation (Dowd-Hinkle, 2012).

A final example is watching movies and TV over the internet, with streaming services like Netflix growing their markets. A previous study (Shehabi, Walker & Masanet, 2014). indicated that streaming movies can lead to net energy and carbon savings compared to DVDs. Streaming movies were particularly better than any movie viewing method involving a consumer driving to a store to purchase or rent a DVD. The research found that most of the energy consumption occurred with the equipment a consumer used to play a DVD or stream a movie, and with personal travel to acquire a DVD. If all DVD viewing that occurred in 2011 was streamed instead, roughly 2 billion kilograms (kg) of carbon dioxide emissions would have been prevented (Shehabi, Walker & Masanet, 2014).

Why Consider This?

All these studies show that consumers have the power to reduce their environmental impact through their choices when consuming media. What people do, as individual consumers and also as large organizations, have some form of environmental impact. But as industrial and consumer systems change, their impacts change as well, both in where the impact is and how severe it is. As these changes happen, consumers, companies and industries can make choices that may have a positive or negative impact on the environment. People and companies can have power over their health and environmental impacts by measuring those impacts and making choices based on that.

Considering these examples, games, like other entertainment mediums, are worth studying using LCA methodology. Published research to date has suggested that digital methods of distribution and consumption of entertainment media have a lower environmental impact than physical objects like discs, except for a single study on games, which showed the opposite. However, the authors suggested further research into this subject is needed, considering how quickly technology is moving and where the market is heading. Their work also focused on distribution in the United Kingdom (Mayers, Koomey, Hall, Bauer, France & Webb, 2014); while this study focuses on the United States.

Additionally, as these studies show, digital means of obtaining entertainment are becoming more ubiquitous across all forms of media. As previously shown, digital downloads now make up more than half of video game sales (Games: Improving the Economy, 2014). However, the information on what this means for our collective environmental impact remains limited as these technologies are still relatively new, and require further study in order to understand and continue to lay a foundation for continuing research.

Research Question and Hypotheses

There were several aspects of the previous study on games that bear further investigation or elaboration: 1) The study is limited geographically, and while my research is also, it does take a different region into consideration, which may have various factors such as travel distance and power mix that could affect the final results. 2) It did not measure actual power consumption of a console in use – instead, power

consumption was assumed based on the specifications provided by the manufacturer (Mayers et. al., 2014). In contrast, my study uses measured power consumption data, described in the following chapter. 3) It looks at only previous generation console hardware, without taking into account newer consoles or the PC gaming ecosystem.

My primary research question is: does downloading and playing a digital video game have a lower environmental impact than purchasing a Blu-ray or DVD on previous generation consoles, current generation consoles and PCs? LCA will demonstrate how environmental impacts compare to each other across platforms and formats. On previous generation console hardware, based on my previous pilot studies, it is reasonable to predict that digital games will result in lower environmental emissions than physical games. However, due entirely to higher power demands on current console hardware and PCs, as well as larger download file sizes, I predict the results will be more mixed to potentially favorable for physical games depending upon the impact category examined. Because of the potential influence of those two factors, energy efficiency of downloads and file sizes are to be tested with sensitivity analysis, described in the following chapter. The sensitivity analyses conducted may make digital downloads more comparable to their physical counterparts on more intensive hardware.

Chapter II

Methodology

In this chapter, LCA as a methodology is explored, as well as specifics of the life cycle modeling, data sources and an experimental procedure.

Life Cycle Impact Assessment

LCA follows a product's life cycle from the point of raw material extraction to the end of its life, and measures all the environmental emissions associated with it. Conducting an LCA requires defining several aspects of a product's life ranging from the function of the product to the system boundaries.

LCA Goal and Functional Unit

LCA entails defining a goal and scope (Baumann & Tillman, 2004). The goal of this study is to compare the impacts of digital video game versus a disc video game starting after a game's development. The scope includes all environmental impacts outlined within the TRACI 2.1 classifications for both the disc and the digital download across three platforms: last generation console hardware (represented by the PS3), current generation console hardware (represented by the PS4), and PC. The Playstation line of consoles was chosen both for researcher convenience, and because the PS4 is the current console market leader (D'Angelo, 2016).

LCA also entails defining a functional unit. The functional unit is the quantification of the service or purpose of the product or good under study. An example is transportation of people or goods. The purpose of transportation, to move people or goods from one place to another, can be quantified as person-distance, such as person-miles or person-kilometers (km) (Baumann & Tillman, 2004). For mass it can be expressed as mass-miles, or kg-km.

For this study, the product is a single video game. The functional unit is defined as a single video game being moved from distribution to consumer after the game's development cycle. This is similar to the functional unit used by Weber et. al. in their study on music, where they defined the functional unit as a single complete album of music (Weber et. al., 2010).

TRACI 2.1: Normalization, Categorization, Classification, and Weighting

Once LCA is conducted, impacts are contextualized through classification, characterization, weighting and normalization. Classification is putting impacts into categories, such as fossil fuel depletion. Characterization is the actual calculation of each impact per category, such as amount of fossil fuels depleted. Normalization is using a reference value for impact assessment. An example is relating the impacts of a single product to the total impacts of the region where it was consumed as a percentage. Weighting is putting each characterized result into the aggregate whole (Baumann & Tillman, 2004).

These steps are done using an impact assessment framework. For this study, the TRACI 2.1 framework, developed by the U.S. Environmental Protection Agency, is

utilized. TRACI 2.1 normalizes LCA results within the total impacts of the U.S., making it suitable for LCA studies conducted in the U.S. such as this one. It classifies, characterizes and weights impacts using the following set of impact categories:

- Ozone depletion: the potential of emissions to damage the stratosphere's ozone layer, characterized as ozone depletion potential (ODP).
- Global warming: the contribution of environmental emissions towards climate change, characterized as kg CO_2-equivalent (eq.)
- Acidification: emissions that result in an increase of the concentration of positive hydrogen ions, causing local acidity. This is measured in kg sulfur dioxide (SO_2) eq.
- Cancer: these are emissions of pollutants that cause cancer in humans, characterized as CTUcancer.
- Non-cancer: these are pollutants that cause health effects other than cancer. Non-cancer emissions are measured as CTUnoncancer.
- Eutrophication: these pollutants contribute to the process of eutrophication in aquatic habitats. These are measured as kg nitrogen (N) eq.
- Smog formation: airborne emissions that can contribute to the formation of ground level smog. These are characterized as kg ozone (O_3) eq.
- Ecotoxicity: This is a measure of pollution in freshwater. Ecotoxicity is characterized as CTUe. (what is CTU – look this up)
- Fossil fuel use: human activities consumes fossil fuels, measured as units of energy in megajoules (MJ).

- Respiratory effects: pollution can have detrimental effects on the human respiratory system. These are measured as kg PM 2.5 eq. (Bare, 2012).

OpenLCA and the EcoInvent Database

The LCA models for this study were built using the OpenLCA software package from Green Delta, a company based in Berlin, Germany (Contact, 2014). OpenLCA allows users to construct processes, such as the manufacture of a product, using data from existing research, their own experiments, or previously modeled data from a database. These processes are built using inputs and outputs, or flows - a process takes in certain materials or activities, and puts out other products or activities. Properties of flows, such as type of material, amount of it, and units can all be configured. Processes can be linked to each other as inputs or outputs to create a chain of processes and carry the environmental impacts associated with that process to the next step in the supply chain (Winter, Emara, Ciroth, Su & Srocka, 2015).

Once the processes are built and linked, users can create a product system in OpenLCA, which synthesizes the data from each involved process. The product system is the life cycle model of the product under study. It enables users to see impacts by different processes and flows, and what impacts occur at what point in the life cycle. Users can go even further with OpenLCA's project and report functions, which pulls in data from one or more product systems and presents different data in charts and graphs. Characterization, classification, normalization and weighting are done within OpenLCA by selecting a normalization and weighting set when creating a product system or project (Winter et. al., 2015). As previously stated, TRACI 2.1 was chosen for this study.

This study used data gathered from previous studies and an experimental protocol (detailed below), for foreground modeling data. Background data, such as emissions produced by electricity production, raw material extraction, manufacturing and other processes are from the EcoInvent database version 2.2. This database comes from the EcoInvent Centre in Zurich, Switzerland (Contact, 2015, Ecoinvent Association). EcoInvent is a database of life cycle inventory data in many economic sectors including energy, agriculture, waste management, transportation and others. The data have been gathered by industrial sources, research institutions, universities, and LCA professionals and consultants (The Ecoinvent Database, 2015).

The Product Life Cycles and System Boundaries

Conducting an LCA entails defining the product system and its boundaries. Somethings that could be included may be left out for a variety of reasons to make a study more feasible, while others are included. Below is a list of some assumptions made for this study, and the system scope and boundaries:

- The manufacture of most hardware, such as televisions, monitors, PCs and consoles were assumed to be equal between all models, and are excluded. The one exception is disc drives needed for physical PC games, as many modern computers do not come with built-in disc drives (Smith, 2013), while they are built-in for modern gaming consoles. Disc drive manufacture was included for physical PC games. That system was also studied without it.
- The electricity consumed by a television or monitor running a game was excluded, as the electricity consumed by the screen was assumed to be the same

independent of what is showing on it. Electricity consumed by a console or PC running a game was included. Change all past actions and results to past tense, --in Results also

- Emissions from activities involved in a game's development, such as script writing, motion-capture, voice work, programming, art design and others are assumed to be the same between all formats, and are excluded from the study's scope.
- For this study, the manufacture of servers for online stores and total energy consumed by them is considered an embedded emission. Their energy consumption and subsequent emissions as immediately relevant to digital downloads will be included.
- Similarly, emissions from other infrastructure will be excluded. This includes emissions from electricity consumed to run facilities involved in manufacture and distribution, administrative offices, and the manufacture of vehicles for transportation (Mayers et. al. 2014).
- Cumulative impacts from all games sold in the U.S. are not part of this study. This is a one-to-one comparison using averages.
- Energy consumed by servers used for online play is excluded.
- Creating a master copy of a Blu-ray or DVD-ROM from which all others are copied from are assumed to be negligible within the context of how many copies are made. This assumption was also made in Mayers et. al.
- Uploading master data onto servers for consumer downloads is assumed to be negligible.
- Consumers buying physical games travel to the retailer by car in the U.S.

- Even after a consumer finishes playing a physical game, it is assumed that the game may be resold, lent informally to friends and family, or ultimately kept by the consumer as part of a collection. End-of-life is thus excluded from scope, even though at least some games do get disposed of. A similar assumption is also made by Dowd-Hinkle for the study on books and e-readers.

Each different video game format and platform is built using its own set of processes. The below flow charts are the basic life cycles of each modeled scenario. These are based on and modified from similar charts in previous research (Mayers et. al., 2014).

Figure 1 shows a boxed console game and its three basic life cycle stages: manufacture, transportation and use. A solid box or line indicates something included in the scope of this study, while a dotted box or line indicates it is excluded.

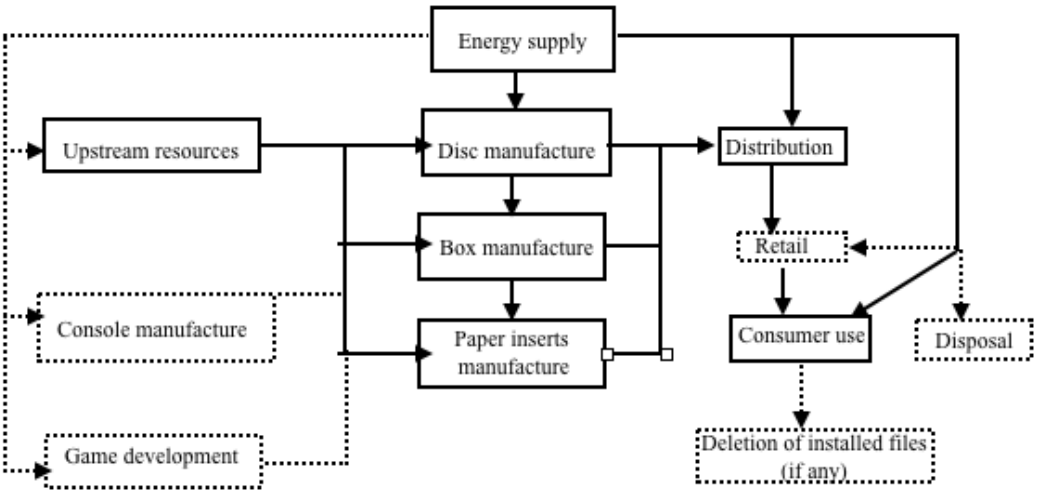

Figure 1. Basic life cycle of a boxed console game (by author).

Figure 2 shows the life cycle of a boxed PC game. It is largely similar to a console game, with one notable difference. The PC game includes the manufacture and

transportation burden of a specific piece of hardware – the DVD drive. For the PC cases that exclude the DVD drive, the life cycle is the same as the boxed console game.

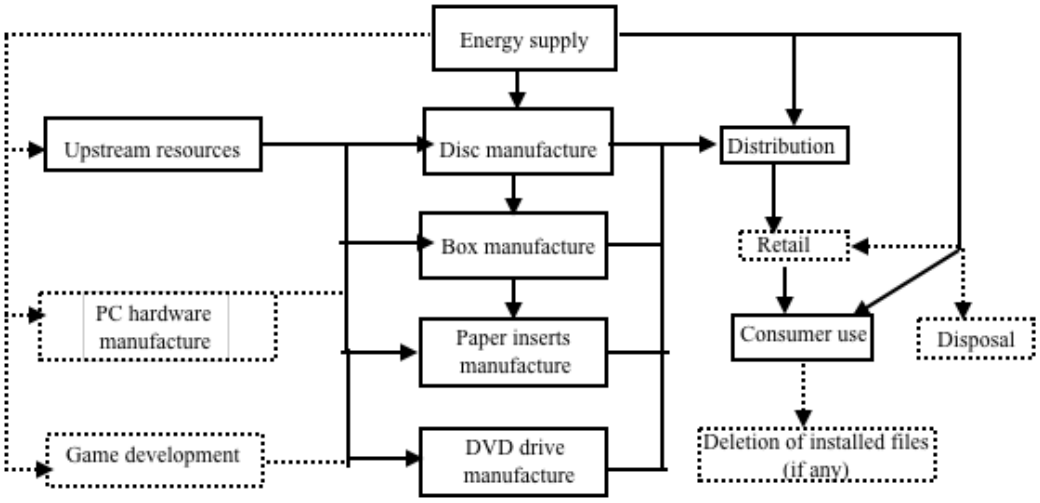

Figure 2. Basic life cycle of a boxed PC game with the DVD drive included (by author).

Figure 3 shows the last modeling case – the digital download. This model looks the same regardless of the gaming platform.

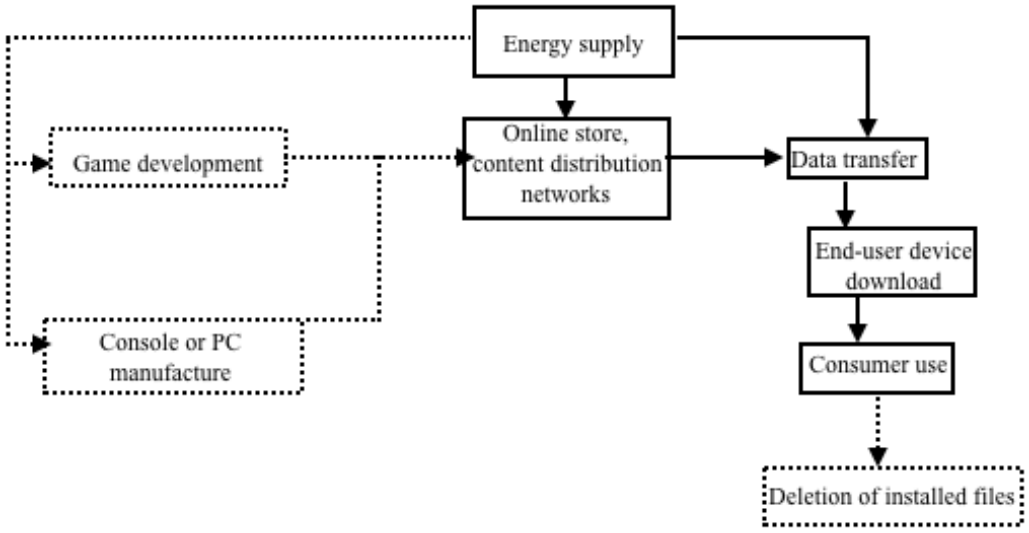

Figure 3. Basic life cycle of a digitally downloaded game (by author).

The first process for Blu-rays and DVD-ROMs is the manufacture of the items themselves. Sony manufactures Blu-rays, including games for its Playstation consoles, in the U.S. in Indiana and they are distributed nationwide from there (Sony DADC Locations, 2015). Previous research measuring carbon impacts of games contained detailed information on the composition of audio-visual media, such as materials and volumes for the different components of discs and the equipment used to transport them (Mayers et. al., 2014).

Next is the distribution and transportation phase. In OpenLCA, the outputs of the manufacturing process are linked to the transportation phase as an input, which brings everything from the manufacturing phase into the next phase. Methods of transportation as well as the average distance traveled were chosen based on previous research and data from the United States Department of Transportation, detailed later. The distribution phase also includes consumer travel to a retailer to purchase the product. The output of this process, the game reaching the consumer, is linked as an input to the next phase, use.

The use phase, consisting of gameplay, is built with electricity consumption required to run the game over the time the game is played. These data are gathered with an experiment. The output, a consumed game, is the product endpoint, and all this can be linked together and synthesized in OpenLCA (Winter et al., 2014).

A digital game has a different life cycle within the OpenLCA modeling process. The first major phase is purchase, download and installation by a consumer. The electricity associated with data transfer over the internet is entered as an input. A study published in 2014 assessed the impacts of data transfer over the internet using LCA. This is used for data on electricity consumed by file transfer from server to consumer (Malmodin, Lunden, Moberg, Andersson, & Nilsson, 2014).

The use phase, gameplay, is modeled the same way as a physical game, using electricity inputs and hours played. Like with physical games, once the processes are built they are synthesized into product systems. They are pulled into summary reports with OpenLCA's project and report functions for comparison. These reports display the data in charts and graphs to compare impacts by category and product system (Winter et. al., 2014).

Foreground Data Sources

LCA models in OpenLCA are built based on unit processes. The data to build those processes was gathered from a variety of sources, described below.

Experimental Procedure

This study includes an experimental component to test whether there is a difference in the energy consumption needed to run a Blu-ray disc game or a digitally downloaded game during gameplay. There are reasons to believe a digitally downloaded game is more energy efficient during gameplay, depending on how the hardware and software behave together. Running a Blu-ray uses a console's laser disc reader to read game data, which is less efficient than reading data from its hard drive during gameplay. This works differently from a downloaded file, which installs directly to the console hard drive and data are read from there, bypassing the laser disc reader. It is also more efficient to process data from a hard drive than a disc reader. This efficiency benefit is why newer consoles are now programmed to install disc files straight to the hard drive, but still require the disc to access the files (Totilo, 2013).

If it is more expedient to read data from a hard drive than a disc, it may follow that this leads to a higher power draw for running a game directly from a Blu-ray disc. This difference in power draw during gameplay may have some impact on the LCA results. Previous studies have assumed that the difference, if it exists, is negligible (Mayers, et al., 2014). This can be tested experimentally by measuring power consumption during gameplay between a digital and disc game using a Kill-A-Watt (KAW) reader. Power consumed by other processes such as file download and installation from download or discs onto console or PC local storage can be measured the same way.

The KAW is a tool developed by the P3 International Corporation in New York City, New York. It can measure electricity draw of home appliances. It works by

plugging an appliance into the KAW, and then plugging the KAW into a power outlet or power strip. The KAW can measure the electricity consumption associated with the plugged in appliance within 0.2% accuracy. The KAW also keeps a cumulative reading of total kilowatt-hours (kWh) of power drawn for as long as it is plugged in or until it is reset (Kill-A-Watt, 2015).

The experiment is conducted by plugging a PS3, PS4 and gaming PC into the KAW and taking readings for power draw from the KAW to use in the LCA modeling. Electricity data is recorded for file download, installation and gameplay of different games for data to use during the LCA use phase. Games are selected in order to be available across at least two of the gaming platforms to ensure the same software is running on all relevant hardware.

Spreadsheet workbooks are created by platform and format, with different sheets for each game. Wattage is read and recorded in the corresponding spreadsheet (such as PS3 Blu-ray workbook, *Bioshock Infinite* sheet) at random intervals during gameplay, and a short description of in-game events at the time of reading is noted. This is to ensure a representative capturing of in-game processes to reflect the full range of power a console or PC may be drawing from moment to moment. An equal number of observations are taken for each corresponding gameplay session, and games are played for an equal amount of time. If watts are recorded in a spreadsheet 23 times during one hour of gameplay in *Bioshock Infinite* on a PS3 Blu-ray, it is recorded 23 times during gameplay as a PSN download and on PC. Accumulated kWh from the KAW is recorded at the end of each session, and the KAW itself is reset to be ready for the next experimental session.

At the end of the experimental period, wattage and kWh from all gameplay sessions are averaged on a game-per-format basis - for example, all kWh readings for *Bioshock Infinite* sessions on the PS3 Blu-ray were averaged together. Then, *Bioshock Infinite's* average on PS3 Blu-rays are averaged with all other games on PS3 Blu-rays. The total average kWh figures are entered as electricity inputs in OpenLCA during the use phase process for each different format and platform.

The PS4 takes a somewhat modified approach. As it automatically installs data from a Blu-ray onto its a hard drive as previously noted (Totilo, 2013), a single-format experimental approach, retail discs, is used for the PS4 under the assumption that power draw would not differ between formats. This approach is supported by a pilot project I conducted prior to this study. One game I tested before this study on my PS3, *Far Cry 3*, installed approximately the same amount of data from the disc onto the hard drive as the digital download installed. The power consumption results for gameplay of each format were subsequently roughly equivalent (Buonocore, 2014). As disc drives are built into all current generation gaming consoles, discs create no additional hardware manufacturing burden on console platforms.

PC games also have some additional notes. Like console games, PC games are available both as boxed optical disc releases on DVD-ROM and digital downloads from online stores. The Steam platform is one such store, run by Valve Corporation in Bellevue, Washington (Contact, 2015, Valve Corporation). It enables users to purchase digital copies of PC games, and download and install them onto their computer (Welcome to Steam, 2015). It is the largest PC gaming platform; as stated previously, in February 2015, Steam surpassed 125 million accounts (Plunkett, 2015). Disc PC games

install all their files directly to the computer hard drive, and this has been the case for several generations of PC gaming (Installation and Maintenance of Games, 2015). It will therefore be assumed that power consumption per hour of gameplay in the use phase on PC will be the same whether a game is purchased as a disc or download. PC games are tested only in a single format as Steam downloads.

It is important to note that unlike consoles, equipment associated with physical games for PC use differs. PC games on a disc require hardware that digital-only games do not require - a disc drive, either built-in, or an external drive connected via USB or other connection. Disc drives are no longer included on many store bought computers and components for home PC builders, which creates an additional hardware manufacturing burden for those playing disc-based PC games (Smith, 2013). However, once a drive is acquired, it can be reused. Thus, the PC physical case is modeled with and without the burden of manufacturing and distributing the DVD drive. To model that burden, existing EvoInvent 2.2 data is used.

The electricity consumed by a PC game is further averaged using data from Valve, existing studies on computer hardware and some tools used by PC gamers and builders. Unlike consoles, where hardware is standardized, PC hardware is highly variable. Users can customize all the hardware on a PC, with a wide range of central processing units (CPUs), random access memory (RAM) and graphic processing units (graphics cards or GPUs) available on the market to fit a variety of budgets and needs. The hardware setup of a given gaming PC can also have a considerable impact on the amount of power consumed by it (Mills & Mills, 2015).

Mills and Mills found that energy use in individual PC components is highly variable. In some hardware they tested, such as RAM, they found that performance has been going up with efficiency, resulting in more processing but lower energy consumption. Overall, they found that the hardware required for a gaming PC is very powerful, but much of it is highly power intensive, though also comes with some settings that can enhance energy efficiency. However, consumers are often ill equipped to make wiser energy decisions when choosing PC parts, with few standards available and marketers and salespeople not providing this information or having it in hand. In their tests of different hardware setups, they did find that higher levels of power efficiency could be achieved without negatively affecting desired performance by changing both hardware and its operational settings (Mills & Mills, 2015). While it is beyond the scope of this study to look at computer hardware itself in detail, Mills and Mills demonstrate that it is integral to somehow account for hardware variation when looking at PC games from a life cycle perspective.

Valve conducts a randomized monthly survey of Steam members to gather data on the hardware and operating systems of its users (Steam Hardware & Software Survey: February 2016, 2016). My PC, which was used to test games, may not be representative of the average user's PC setup. The experimental data in conjunction with Valve's survey and a power consumption calculator available on online retailer Newegg.com are all used to approximate the average energy consumption of a PC during use. Exact methods are detailed later.

For these reasons, the amount of gameplay time captured varied across platforms. The PS3 is the only platform experimented on where physical and digital distribution

have the potential to effect the use phase. Thus, time captured for gameplay is as follows:

- For PS3, each selected game was played for 10 hours as a digital download and on a disc, resulting in 10 hours of gameplay per game per format, 20 hours total of gameplay per game, 50 total hours per format, and 100 hours total.
- For PS4, each game was only played for 10 hours as a single format on a disc, resulting in 50 hours total.
- For PC, all ten games were played for 10 hours total in a single format as a Steam download, resulting in 100 hours total.

Five games are selected to reflect the last generation of gaming hardware and software: *Bioshock Infinite, Far Cry 3, Saints Row 2, Batman: Arkham Asylum* and *Borderlands 2*. These games reflect various aspects of game design, gameplay style and worlds in modern gaming, with this list including games that are third- and first-person, and games that are open world and linear. Current generation games are reflected in the following titles: *Far Cry 4, Middle-Earth: Shadow of Mordor, Alien Isolation, Watch_Dogs,* and *Wolfenstein: The New Order*. These games are selected for the same reasons. It is worth noting that new game generations are adopted slowly; even as the PS4 dominates its markets, consumers will be able to easily buy PS3 consoles and PS3 games into the future. The same applies to Microsoft's Xbox One and Xbox 360. Additionally, some games out on the new consoles are also available on each console's respective predecessor and PC (Brown, 2014). As the console generation and technology is forging ahead, including each for this study is important in order to reflect a gradually shifting market.

Other Foreground Data

The data gathered in the experimental procedure did not provide all the information necessary to build complete LCA models. Other sources were consulted for data ranging from transportation of goods between manufacture and consumer, electricity use of internet infrastructure, and how optical media like DVDs and Blu-rays are manufactured.

A physical packaged Blu-ray or DVD has three primary components - the disc(s) itself, the case and a paper insert. For life cycle assessment, the amounts of each of these three components are included in the analysis. The largest component by mass is the case at 66 grams (g) according to Mayers et. al. The material is polypropylene plastic (Mayers et. al., 2014). Injection molding will be assumed for shaping the material.

The second largest component is the disc, which is more complex. The total mass of a disc is 17 g (Mayers, et. al, 2014). The primary component of an optical disc is polycarbonate, a type of plastic, which is shaped and sized with injection molding. The data is not etched into the plastic itself, but a layer of silver or aluminum alloy on the bottom. Most discs for games also have a thin resin cast on top for cover artwork. The entire disc is 1.2 millimeters (mm) thick. However, the size of the metallic layer varies between Blu-rays and DVDs, and this difference is important to this study due to physical PC games using DVDs instead of Blu-rays. The metallic alloy on a Blu-ray disc is 0.1 mm thick, while on a DVD, it is 0.6 mm thick (Sharpless, 2009). This makes the metallic layer 9% of the thickness on a Blu-ray, and 50% of the thickness on a DVD. For the purposes of this study, it will be assumed that those percentages also correlate to the mass

of these materials as part of the total. The calculations below estimate the mass of metallic alloy on both a single Blu-ray and a DVD disc:

Blu-ray: 17 g * 0.09 = 1.53 g metallic alloy per disc

DVD: 17 g * 0.5 = 8.5 g metallic alloy per disc

As no reliable data can be found on the type or amount of material for the resin artwork, this is left out of the study and assumed to be negligible. Base case modeling uses aluminum for the alloy.

The final component is paper. Most optical media includes a paper insert, averaging at 6 g (Mayers et. al.) However, no reliable data is available on exactly what type of paper such inserts are made of. For modeling purposes, a generalized coated, wood-free graphic paper from EvoInvent has been chosen as a proxy.

Once manufactured, the game has to travel from the point of manufacture to its destination, the consumer. Shehabi et. al., which looked at distribution of optical discs for movies and TV shows compared to streaming, used a figure of 1825 km based on previous research. They assumed an evenly broad network for distribution centers and retail outlets in the U.S. for this figure. This figure, and its assumptions, are also used in this study. Additionally, it is assumed that physical games are transported between manufacture and retail by truck. Most freight in the U.S. is carried by truck, whether measured by tonnage or value (Bureau of Transportation Statistics, 2016), forming the basis of this assumption.

For getting the game to a consumer digitally, there is no physical manufacturing system. Energy is required to move data from servers through internet transfer infrastructure to the consumer's end device. The study conducted in Sweden by

Malmodin et. al. found general averages for the electricity necessary per gigabyte (GB) of data downloaded. These figures are assumed to be accurate for any data transmission network in a developed country, including the U.S., for the purposes of this study.

Starting at servers at a data center, 1 kWh of electricity is required per GB of data downloaded. At the data transmission IP core network, the consumption drops to 0.8 kWh/GB. Access network transmission is also 0.8 kWh/GB. Customer equipment to access the network like a router is calculated at 0.3 kWh/GB (Malmodin et. al. 2014). The end user device is measured using the experimental procedure with the KAW tool, and was averaged using the same method as gameplay data, which is described below.

The other data point necessary for estimating total energy usage in data transfer is the amount of data being downloaded. Game file size varies greatly, ranging from small indie titles not even reaching 1 GB and others over 40 GB (Complete list of PlayStation 4 game install sizes – over 460 titles, 2016). Because of the wide range of file sizes, this study uses averages. For the PS3 console, file sizes are averaged from three different sources. The first is the average used by Mayers et. al. of 8.8 GB, based on top selling games from 2010 (Mayers et. al. 2014). The second is a list of titles that came out in 2013 that were available on both the PS3 and PS4 at launch, such as *NBA 2K14* and *Call of Duty: Ghosts* (Brunner, 2013). The third is from the experimental procedure, which recorded download sizes for each game used experimentally as listed on the Playstation Store. This calculation produced an average file size for PS3 of 7.9019 GB.

For PS4, a running list of all available games for the console, including indies, has been kept at Finder.com. As of this writing, the list was last updated on January 29, 2016 (Complete list of PlayStation 4 game install sizes – over 460 titles, 2016). It is assumed

that games released after that date will not significantly alter the average. This list is imported into a spreadsheet, and an average is calculated from all titles listed as "major," under the assumption that the majority of indie games do not see physical disc releases, nor sell as well as most games from better known studios. The calculated file size average for the PS4 is 14.3174 GB.

For the PC case, an article on PC Gamer compiled 28 of the best-selling PC games since 2007 and charted a trend of growing file sizes. File size spiked around the year 2013, coinciding with the new console generation (PC Gamer, 2015). File sizes of each listed game is estimated based on PC Gamer's bar chart, and put into a spreadsheet along with all the games used in the experimental stage. The download sizes for experimental games are recorded from Steam during download, and some overlap is present between PC Gamer's data and the experimental data. An average file size is calculated at 19.3907 GB, presenting the largest file size for all base modeling cases.

However, file size has an impact on modeling beyond just digital distribution for the PC scenario. As stated above, Blu-rays are not used for PC software as DVDs are favored. DVDs do not have as much data storage capacity as Blu-rays. DVD storage capacity ranges anywhere from 4.7 GB to 17 GB, depending on layers of data and how many sides of the disc are utilized (PC Mag, 2016). Regardless of which format of DVD is used, more than one disc is required to store all the data of a game that is over 19 GB in size. For this study, it will be assumed that the 4.7 single-layer single-sided DVD is the most commonly used format. Under that assumption, a minimum of 5 discs are required to store a 19.3907 GB game.

The bulk of data for the use phase for both physical and digital distribution is gathered in the study's experimental procedure. However, some further research is necessary for each modeling case to quantify life cycle impacts for this step. One aspect of this is how long the average game is played. The study conducted by Mayers et. al. provided some data on this, which is used in this study. The researchers found that the first use of a game is 158 hours, which excludes both formal reuse, such as selling a game, and informal reuse such as lending among friends and family. Once reuse is factored in, the average gameplay time climbs to 232 hours. These figures are distorted upwards by heavy gamers (Mayers et. al., 2014).

232 hours of total gameplay time is used for the console physical cases. As there is no reuse system for digitally downloaded games, the 158 first-use figure is used there. Additionally, the 158-hour figure is also used for physical PC games. This is because physical PC games and other computer software typically requires an activation code (Recover Lost or Forgotten CD Keys or Serials for Your PC Games, 2013). The intent is to combat piracy, but lost or single-use activation codes prevents both a used game market from forming and informal lending.

The other consideration for use phase is bringing power consumption data measured during experiments into an average. This is due to hardware variations, particularly on PC. However, during their life cycles, consoles can also go through some hardware evolution that can affect their power consumption, described below.

For the sake of this study, the PS3 is divided into two fundamental models - the PS3 "fat" and the PS3 "slim." The fat models were early in the console's life cycle, first available in 2006 in Japan, and the following year in Europe. The slim models came out

in 2009 (Yin-Poole, 2013). The PS3 slim featured design changes that increased the console's energy efficiency. Some tests found the slim models consumed less than 50% of the electricity of older fat models (Moskovciak & Katzmaier, 2009).

Using that information, as well as the experimental data (gathered on a PS3 slim model) it is possible to estimate an average figure of energy consumed when running a PS3. Using the data from Moskovciak and Katzmaier from CNET on power consumption of the fat PS3 model in both gameplay modes, a fat PS3 model consumes roughly 205.37 watts (W) to run a game. This is a consumption of roughly 0.2054 kWh per hour of gameplay time. Experimental data gathered on a slim model calculated average energy consumption of 0.0794 kWh/hour for discs and 0.0724 kWh/hour for digital games.

In order to estimate the PS3's average power use in kWh while taking different models into account, the energy consumption figures from the experiment and external sources can be added together then divided by two.

Discs:(0.2054+0.0794)/2=0.1424

Digital:(0.2054+0.0724)/2=0.1389

These figures are estimates and do not take sales rates of the different models into account. Calculating a more precise figure is beyond the scope of this study, but it is worth accounting for the difference between the PS3's models in some manner.

The PS4 has also already gone through some hardware revisions even though it less than three years into its life cycle as of this writing. There are currently three PS4 models on the market. An average figure of energy consumption for the PS4 can be calculated using a similar method for the PS3. As with the PS3 case, experimental data

will be used, in this case for energy consumption of the first model of the PS4. The energy consumption of the two models out after it have been calculated in other experiments. The second model consumed 141.3 W while running games, and the third model 122 W in active gameplay (Arif, 2015). This comes to roughly 0.1220 kWh/hour of gameplay for model 3, and 0.1413 kWh/hour of gameplay for model 2. Experimental data measured the model 1 PS4 at 0.1168 kWh/hour of gameplay. By adding these together and averaging them, an estimated figure comes to 0.1266 kWh/hour of gameplay ((0.1220+0.1413+0.1168)/3=0.1266).

The PC case is far more complicated than either console generation to average. The hardware, such as the graphics technology and processors, that goes into gaming consoles is standardized. PC hardware is much more variable. Two computers can have an entirely different set of hardware specifications, ranging from processors to GPUs to RAM. And as studied previously, the hardware a given PC is built with can have an impact on how much energy the machine consumes, with different individual pieces of hardware requiring various amounts of energy to work (Mills & Mills, 2014).

Despite the variability, it is possible to estimate and average for the purposes of modeling use phase electricity consumption of PC gaming using a few different resources. The first is the experimental data, gathered on a PC with the following hardware specifications:

- Hard drive: Crucial MX100 512GB SATA 2.5" 7mm Internal Solid State Drive CT512MX100SSD1
- Motherboard: Gigabyte LGA 1150 H97 Wi-Fi Bluetooth HDMI SATA 6Gb/s USB 3.0 Mini ITX Intel Motherboard GA-H97N-WIFI

- CPU: Intel Core i5-4590S BX80646I54590S Processor (6M Cache, 3.3 GHz)
- RAM: PNY XLR8 16GB (2 x 8GB) DDR3 1600Mhz CAS CL9 Desktop Memory Module-MD16384KD3-1600-X9
- Graphics card: PNY XLR8 NVIDIA GeForce GTX 970 4GB GDDR5 Graphics Card VCGGTX9704XPB

No disc drive is installed on the experimental PC.

The second resource necessary for bringing the experimental PC data into an average is a calculator provided at online technology retailer Newegg.com. Users can input hardware specifications into the calculator, and it will give an estimation of the maximum wattage the machine will use. This tool provides consumers building PCs with a guideline for the power supply they will need to run their machine. By putting the specifications listed for the experimental machine, Newegg's calculator estimates power consumption of the experimental PC as up to 549 W, with a screenshot of the calculator in Annex 1 (Newegg.com).

The final resource is from Valve Software. Each month, Valve conducts a randomized survey on Steam to gather data on the hardware and software its users have on their PCs. Using this, it is possible to put together a snapshot of the average PC gamer's hardware setup, and using Newegg's tool, estimate how much power the average machine uses at its theoretical max. The data used in this study is from Valve's February 2016 survey (Steam Hardware & Software Survey, February 2016, 2016).

Once this information is gathered, the power consumed by an average PC can be estimated. The experimental data can be measured as a percentage of the theoretical

maximum power consumption calculated for the experimental PC by the Newegg calculator. This percentage can then be applied to theoretical maximums of the other hypothetical PCs, and then those percentages can be averaged together. This method is not precise and leaves out a great deal of possible hardware setups, but for the purposes of this study, it is assumed this small sample of possibilities will provide a reasonable estimate for the power consumption in the use phase of playing video games on a PC, accounting for low, medium and high powered hardware.

The energy consumption calculated by the Newegg tool are as follows (all figures in watts):

549, 377, 407, 407, 377, 376, 391, 421, 536, 518, 618, 593, 542, 461

Screenshots of each PC calculated by Newegg can be viewed in Annex 1.

Newegg calculated the experimental PC as having 549 W at theoretical maximum power. The experimental data averaged 0.1742 kWh/hour of gameplay, or 174.2 W. 174.2 W is roughly 31.73% of the theoretical max. Applying this percentage to Newegg's figures for other PCs, a reasonable estimate of power consumption in normal use can be estimated. The estimations from Newegg are converted into kWh, and then averaged produce a figure of 0.1490 kWh/hour of gameplay. This figure is lower than the average calculated from just the experimental PC, which is higher-powered and as a result, more energy intensive than the average machine and ranges from Valve's survey data.

These averages have uses beyond gameplay data. As described earlier, the end user device is part of the digital distribution ecosystem and process. The experimental data gathered includes the power consumed by a console or PC in active download mode,

and like gameplay data, this has to be averaged for each case. The average for power consumed can be estimated by comparing the gameplay experimental data to the gameplay's averaged figures as a ratio, and applying that ratio to the experimental download data. Like with the averages for gameplay, this is not a perfectly accurate measure, but for the purposes of this study it will be assumed this provides a reasonable estimation for average power consumed in active download.

Experimental data for the PS3 slim console calculates that it consumes approximately 0.0063 kWh per GB of data downloaded. To account for the fat PS3 model in the download average, the 0.0063 figure can be part of a ratio with the experimental gameplay data and its averaged figure for both disc and digital games, like below, where X is the average figure for energy consumption as a download on a fat PS3:

Using physical gameplay averages

$$0.0794/0.1424 = 0.0063/X$$

$$0.0794 * X = 0.1424 * .0063$$

$$X = (0.1424 * 0.0063)/0.0749$$

$$X = 0.0112$$

Using digital gameplay averages

$$0\ .0724/0.1389 = 0.0063/X$$

$$0.0724 * X = 0.1389 * 0.0063$$

$$X= (0.1389 * 0.0063)/0.0724$$

$$X = 0.0121$$

This does provide two slightly different figures, but they are added together with the experimentally calculated 0.063 figure and divided by 3 to come to average for energy consumption in downloading, taking both models into account:

$$(0.0112+0.0121+0.0063)/3 = 0.0075$$

Largely the same method can be applied to the PS4 to estimate its power consumption in downloading when accounting for the different hardware versions. The PS4's experimental data on a model 1 found it consumed around 0.0061 kWh/GB of data downloaded. X is again an estimated figure for the energy consumed by a PS4 downloading data, in kWh per GB. The ratios are: This comes to roughly 0.1220 kWh/hour of gameplay for model 3, and 0.1413 kWh/hour of gameplay for model 2. Experimental data measured the model 1 PS4 at 0.1168 kWh/hour of gameplay.

Model 2

$$0.1168/0.1413 = 0.0061/X$$

$$0.1168 * X = 0.1413 * 0.0061$$

$$X = (0.1413 * 0.0061)/0.1168$$

$$X = 0.0074$$

Model 3

$$0.1168/0.1220 = 0.0061/X$$

$$0.1168 * X = 0.1220 * 0.0061$$

$$X = (0.1220 * 0.0061)/0.1168$$

$$X = 0.0064$$

As with the PS3 case, these are added together with the experimentally calculated data for the model 1, then divided by 3 to for an average:

$$(0.0061 + 0.0074 + 0.0064)/3 = 0.0066$$

This same methodology is applied to the PC, where downloading is experimentally calculated to consume 0.0012 kWh/GB. The ratio equation is:

$$0.1742/0.1490 = 0.0012/X$$

$$0.1742 * X = 0.0012 * 0.1490$$

$$X = (0.0012 * 0.1490)/0.1742$$

$$X = 0.0010$$

X is again the average estimation for the power consumed by an "average" PC downloading data in kWh/GB.

Sensitivity Analysis

LCA commonly includes some uncertainty, and this study is no exception. Uncertainty can be accounted for using sensitivity analysis, which is the practice of changing various input parameters into the system, such as altering values or specific materials. Sensitivity analysis can also be conducted systematically, such as through Monte Carlo analysis, in which random numbers in the system are multiplied by standard errors, and one hundred simulations are conducted to analyze variations in final results (Baumann & Tillman, 2004).

For this study, individual input parameters are altered to test if results would change in any significant way. Two different scenarios are explored for both the physical and digital distribution cases, described in detail below.

In all physical distribution cases, the manufacturing phase is tested for its sensitivity to the type of alloy used in optical disc production. Two alloys are commonly

used in optical disc manufacture, silver and aluminum (Sharpless, 2009). Aluminum is used for base analysis, but for sensitivity analysis, silver is tested. The mass of silver used in optical media manufacture is kept the same as aluminum for each scenario. As PC DVDs require more alloy than Blu-rays as well as more discs, it is possible that the PC physical case will show greater sensitivity to the type of alloy used.

Physical distribution is also tested for its sensitivity to distance traveled from manufacture to consumer. 1825 km is used as the base case, based on recent previous research (Shehabi et. al., 2014). However, another figure of 3400 km is found in older research (Seetharam, Somasundaram, Towsley, Kurose, & Shenoy, 2010). 3400 km is used as one scenario for sensitivity analysis, an increase over 1825 km by approximately 86%. To reflect a reasonable lower-bound of potential transportation distance by decreasing the base scenario an equal amount, a second figure, 980 km, was calculated using a ratio equation shown below:

$$1825/3400 = X/1825$$

$$1825 * 1825 = 3400 * X$$

$$(1825 * 1825)/3400 = X$$

$$X = 980 \text{ (rounded up)}$$

Digital distribution scenarios are tested for sensitivity by looking at two different aspects of the download process - energy use in data transfer and file size. Weber et. al. estimated that energy intensity of data transfer over the internet drops by roughly 30% annually, or 50% every two years, in terms of kWh per GB downloaded in their study on music distribution. These estimations are applied to the figures used here from Malmodin et. al. for energy consumed by internet infrastructure besides the end user

device the data is being downloaded to. Their data is from 2010 (Malmodin et. al.). This study will therefore estimate data transfer energy intensity for non-user end device infrastructure for 2016, and its effects on the overall systems. This means three cumulative reductions of 50% for server energy, core network data transmission, access to broadband, and consumer modems to 1/8 of their base case values. The values respectively become:

Server: base case of 1 kWh/GB of data. 50% every 2 years to 0.125 kWh/GB

Data transmission and core network, broadband access: base case of 0.08 kWh/GB. 50% drop every 2 years to 0.01 kWh/GB

Consumer end modem: base case of 0.3 kWh/GB. 50% drop every 2 years to 0.0375 kWh/GB

Lastly, this study examines file size for sensitivity analysis. The base case study only looks at games that are considered major titles. This ignores the potential influence on download file size of smaller indie games. To assess the influence of smaller downloads, the list of PS4 games from Finder.com is re-averaged with the indie games factored in. The average calculated this way is measured as a percentage of the average of major-only titles. This percentage is then applied to the average file sizes for the PS3 and PC cases, to come up with a representative average for all three scenarios that includes the influence of smaller downloadable games.

On the PS4, this figure is easily calculated from the spreadsheet created from the Finder.com data. When indie games are factored into the average, the file size drops to 7.0135 GB. For the purposes of calculating the influence of smaller games on PS3 and PC games, this figure is calculated as a percentage of the major only figure below:

$$(7.0135/14.31738) * 100 = 49\%$$

When indie titles are factored in, the file size drops to 49% of the average when considering major titles only.

Below are calculations applying the 49% calculation to PC and PS3 games. It is assumed that this figure is applicable across all platforms in order to come to a reasonable estimation.

PS3:

$$7.90192 * 0.49 = 3.872 \text{ GB}$$

PC:

$$19.39065 * 0.49 = 9.501 \text{ GB}$$

These calculations will be used in each case to analyze the digital distribution system's sensitivity to file size when analyzing life cycle impacts.

Lastly, the PC case will have one additional sensitivity case. The base case for PC includes the burden of manufacturing a DVD drive and getting it to a consumer, under the justification that DVD drives are no longer included on many PCs and their parts. However, it is worth considering that once a consumer owns a drive, they do not need a buy another one in order to keep using PC DVDs for as long the drive functions. Thus, a fifth sensitivity analysis is conducted on the physical PC case only, simply removing the manufacturing and transportation burdens associated with the DVD drive.

Chapter III

Results

The comparison of physical and digital distribution varies by both platform and impact category within the TRACI 2.1 framework. Neither distribution method resulted in less emissions overall on each platform, so results will be explored more in depth on a per-platform basis.

Base Case Comparison of Physical and Digital Distribution

It is still possible to draw some general conclusions and make comparisons from an analysis of all platforms. Figure 4 below shows the relative results from OpenLCA of a single video game on all platforms in both physical and digital media. Relative results in OpenLCA sets the case with the highest emissions per category to a value of 100, then measures the other cases as a percentage of that. It is a way to get an overall side-by-side comparison of all cases in all categories in an easily digestible format.

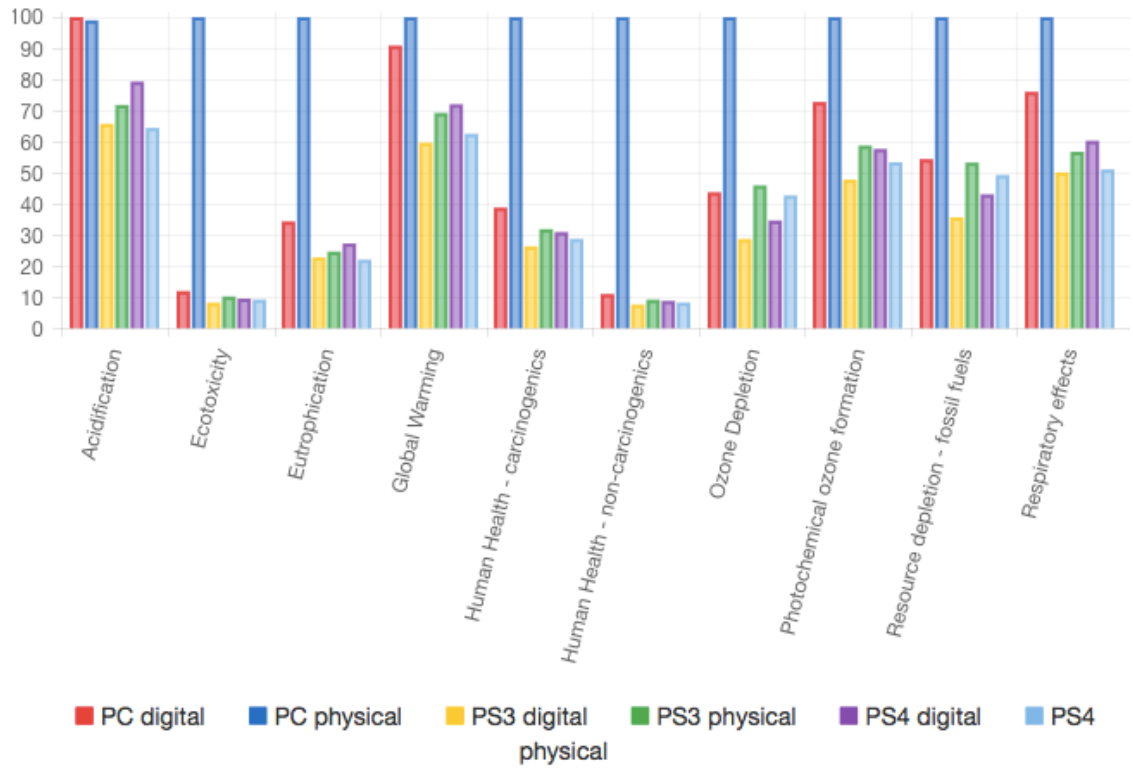

Figure 4. Relative results on all platforms (from OpenLCA).

Neither digital distribution nor physical distribution clearly did better than the other when compared across all three gaming platforms in all TRACI 2.1 categories. However, the poor performance of PC physical games in all categories does stand out, with it being the highest emitter in all categories except for acidification. In that category, PC digital distribution emits slightly more pollution. It is worth noting that the PC physical base case analysis includes the manufacturing and transportation burden of a DVD drive, as described earlier. For a second overall cross-platform analysis, this burden was removed as described previously. The relative results chart of that analysis is below in figure 5.

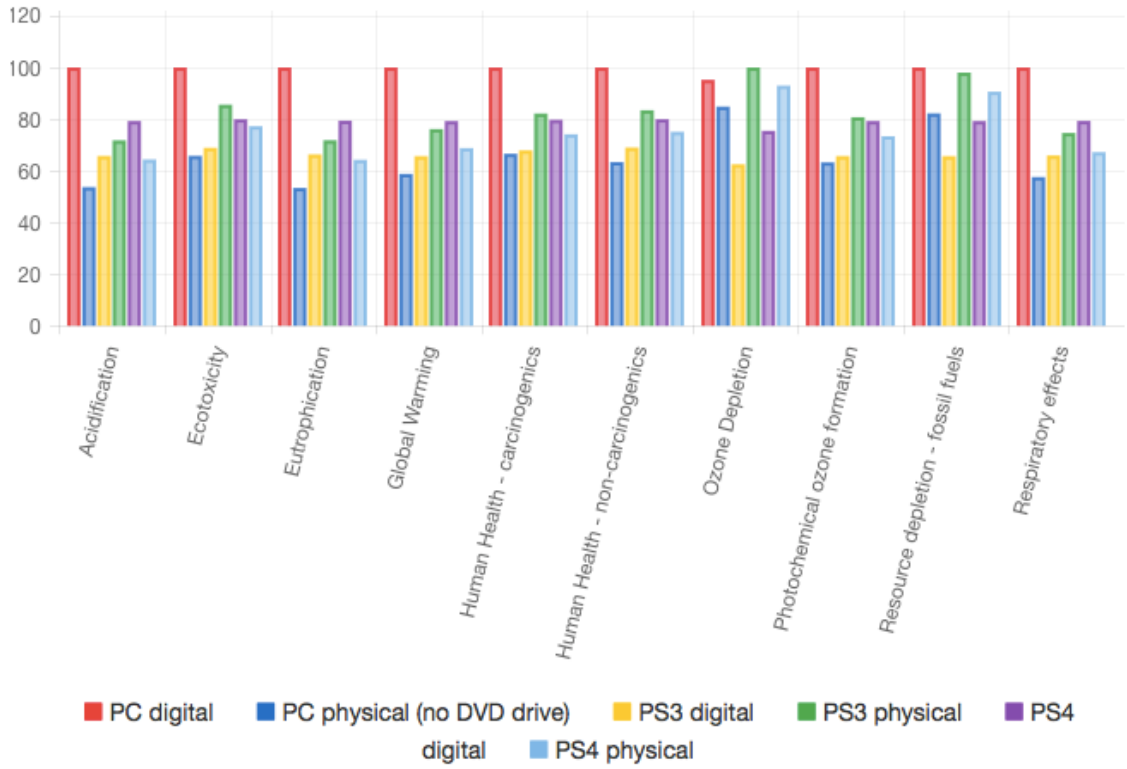

Figure 5. Relative results on all platforms, without the PC DVD drive (from OpenLCA).

This analysis significantly reduces the emissions of the PC physical case in all categories and brings it more in line with the other cases. This shows that the addition of the manufacturing burden of the DVD drive has a significant impact on that case's overall emissions. Once removed for reasons previously described, the PC digital distribution case results in the most emissions across most categories. Ozone depletion stands out as the sole exception, with PS3 physical games overtaking PC digital games.

Overall, on a per impact category basis, neither physical nor distribution comes out as being the less damaging case. It also varies on a per platform basis, particularly in the console cases. In fossil fuel depletion, both consoles perform worse for physical media than digital, but the opposite is true on PC. For respiratory effects, a digital PS4 game outperforms its physical counterpart, but the reverse is true on the previous console

generation and on PC. Thus, it becomes necessary to examine the results on a per-platform basis, and also consider the sensitivity cases.

PS3

For the PS3, digital distribution resulted in less emissions than physical distribution across all TRACI 2.1 impact categories. The chart below in table 1 shows overall LCIA results for both cases on the PS3 platform in all TRACI 2.1 impact categories.

Table 1. LCIA results for PS3 (from OpenLCA).

Impact category	Digital	Physical	Unit
Acidification	1.87220e-1	2.04461e-1	kg SO2 eq
Ecotoxicity	1.19273e+2	1.48187e+2	CTUe
Eutrophication	1.09871e-1	1.18939e-1	kg N eq
Global Warming	2.78283e+1	3.22782e+1	kg CO2 eq
Human Health - carcinogenics	1.75303e-6	2.12166e-6	CTUh
Human Health - non-carcinogenics	5.42548e-6	6.56110e-6	CTUh
Ozone Depletion	1.24484e-6	1.99189e-6	kg CFC-11 eq
Photochemical ozone formation	1.29314e+0	1.58976e+0	kg O3 eq
Resource depletion - fossil fuels	1.63676e+1	2.44336e+1	MJ surplus
Respiratory effects	1.14857e-2	1.30053e-2	kg PM2.5 eq

A single digital download on a PS3 results in roughly 27.83 kg CO_2 eq., while its physical counterpart results in around 32.38 kg CO_2 eq. Physical PS3 games deplete 24.43 MJ (megajoules) surplus of fossil fuels, as compared to its digital equivalent's rate

of 16.38 MJ surplus. A digital game emits 0.109 kg N eq., while the digital version emits 0.1894 kg N eq.

The carbon burden measured here can be compared to what is measured by Mayers et. al. In their study, a PS3 game at 8.8 GB emitted 21.9 kg CO_2 eq. to 27.5 kg CO_2 eq. when downloaded, and 20.8 kg CO_2 eq. as a disc. The digital results calculated in this study are slightly above the upper level of what was previously measured. The physical results here are over 50% higher than what Mayers et. al. measured. This could be due a number of factors, including different shipping methods in the U.S. than in the U.K., where their study was conducted. The U.S. is also a geographically larger area where shipping distances are likely to be higher on average. The experimental procedure for measuring the use phase is also conducted differently in this study. Taking the power difference of running a disc and a download into account would increase the disc's energy burden relative to the digital game's burden. There may be other differences in modeling that are unidentified. Further study on this issue could identify the variables leading to this difference.

These numbers are raw emissions amounts for a single video game. As described previously, they are normalized to the U.S. total emissions, in this case to U.S. emissions in 2008 in TRACI 2.1. This helps to frame all the impact categories within the total emissions of the US for that year, but also more easily compare the impacts to each other. It becomes possible to see in which impact categories a single video game has the greatest and least impact. Figure 6 below shows this.

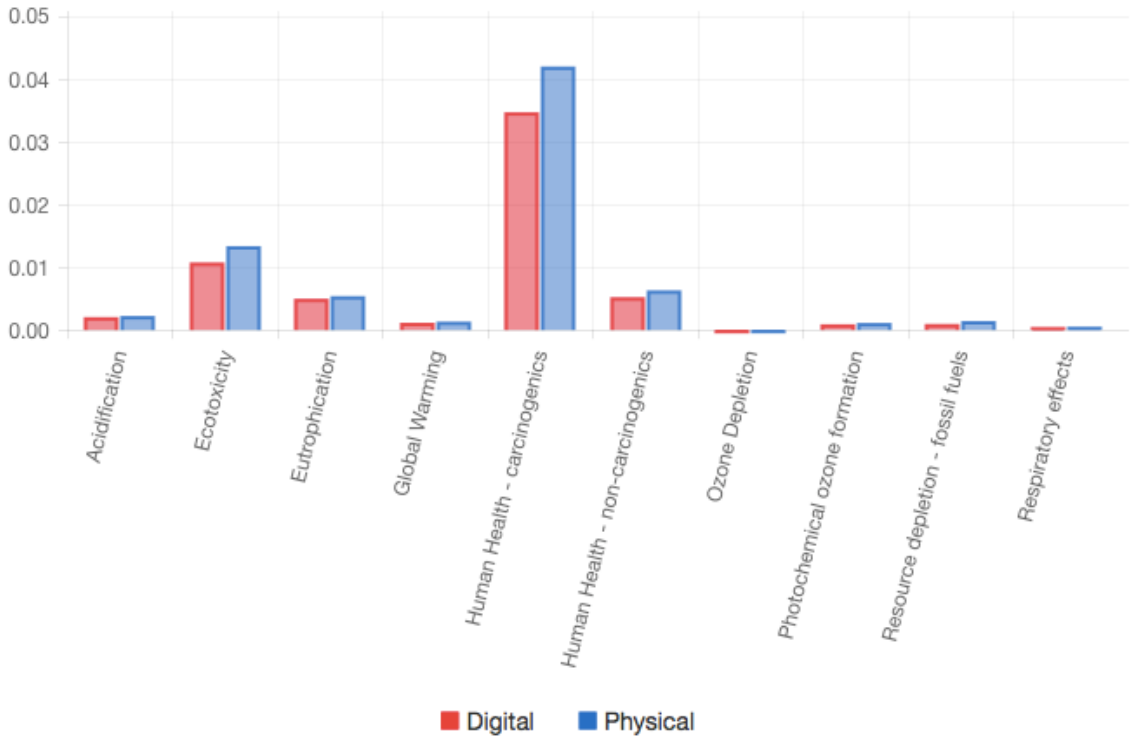

Figure 6. Normalized bar chart for PS3 (from OpenLCA).

Human health - carcinogens immediately jumps out as the category with the greatest impact for video games, with ecotoxicity in second. Ozone depletion and respiratory effects showed negligible impacts for both distribution methods on PS3. Global warming, human health – non-carcinogens, and acidification showed more moderate impacts. This makes carcinogen emissions the point of greatest leverage potential for PS3 video games, if changes were to be made in their upstream processes. In the case of the PS3, digital distribution results in less environmental impacts than physical distribution.

PS4

The PS4 presents a more complicated case than its predecessor. For PS4, digital distribution does not outperform physical distribution in most cases, except for two: ozone depletion and fossil fuel depletion. Table 2 below shows the LCIA results for PS4 games.

Table 2. LCIA results for PS4 (from OpenLCA).

Impact category	PS4 digital	PS4 physical	Unit
Acidification	2.25826e-1	1.83441e-1	kg SO2 eq
Ecotoxicity	1.38434e+2	1.33788e+2	CTUe
Eutrophication	1.31514e-1	1.06416e-1	kg N eq
Global Warming	3.35920e+1	2.91584e+1	kg CO2 eq
Human Health - carcinogenics	2.05905e-6	1.91456e-6	CTUh
Human Health - non-carcinogenics	6.28901e-6	5.90463e-6	CTUh
Ozone Depletion	1.50319e-6	1.85243e-6	kg CFC-11 eq
Photochemical ozone formation	1.56049e+0	1.44470e+0	kg O3 eq
Resource depletion - fossil fuels	1.97589e+1	2.25989e+1	MJ surplus
Respiratory effects	1.38192e-2	1.17092e-2	kg PM2.5 eq

For fossil fuels, physical PS4 games deplete almost 22.6 MJ surplus compared to the digital game's 19.76 MJ surplus. Physical PS4 games emit roughly 0.0000019 kg CFC-11 eq., while digital PS4 games emit 0.0000015 kg CFC-11 eq. These are very small numbers for ozone depletion, so putting them into context through normalization is important. In all other categories the physical game had a small impact than the digital game. These are raw LCIA impacts. In Figure 7 below these impacts are normalized, to make comparison between impact categories easier.

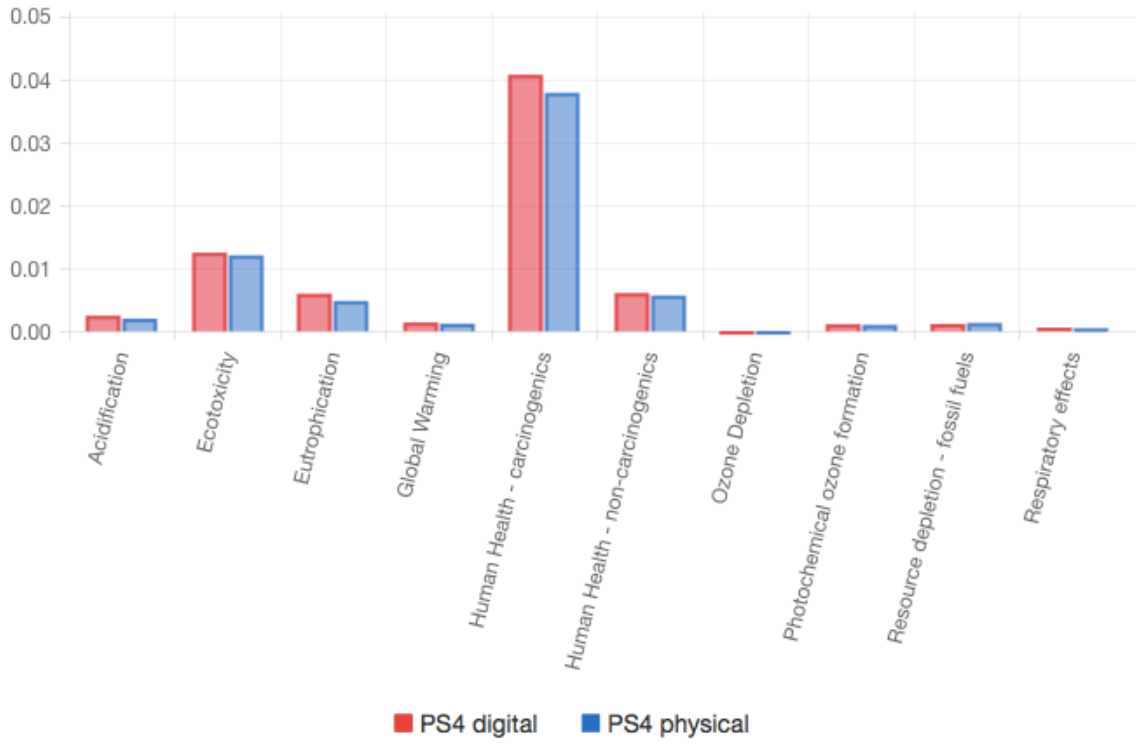

Figure 7. Normalized bar chart for PS4 (from OpenLCA).

In the two categories in which the digital game had a smaller footprint than the physical game, fossil fuel and ozone depletion, the overall impacts are negligible once normalized. Like with PS3 cases, the largest impacts are found in human health carcinogens, with ecotoxicity in second. Moderate impacts are in eutrophication, non-carcinogens and acidification. Global warming impacts are also rather small compared to others.

PC

PC also presents a more complicated case, due to the DVD drive. Table 3 below shows the LCIA impacts for digital and physical PC games, both with and without the

DVD drive. The physical case without the DVD drive is labeled "PC physical SA 5," for it being the fifth sensitivity analysis case.

Table 3. LCIA results for PC (from OpenLCA).

Impact category	Digital	Physical	Unit
Acidification	2.84875e-1	2.81956e-1	kg SO2 eq
Ecotoxicity	1.73121e+2	1.45011e+3	CTUe
Eutrophication	1.65620e-1	4.82575e-1	kg N eq
Global Warming	4.23825e+1	4.66527e+1	kg CO2 eq
Human Health - carcinogenics	2.58204e-6	6.66000e-6	CTUh
Human Health - non-carcinogenics	7.86252e-6	7.14217e-5	CTUh
Ozone Depletion	1.89670e-6	4.33967e-6	kg CFC-11 eq
Photochemical ozone formation	1.96871e+0	2.70751e+0	kg O3 eq
Resource depletion - fossil fuels	2.49299e+1	4.58723e+1	MJ surplus
Respiratory effects	1.74228e-2	2.29258e-2	kg PM2.5 eq

Digitally distributed PC games clearly outperform physical games when the DVD drive is included. The only category in which PC DVDs have a smaller footprint when the drive is included is acidification – 0.285 kg SO_2 eq. for digital, 0.282 kg SO_2 eq. for physical, a very small difference. However, once the drive is excluded, PC physical games outperform digital games across all of TRACI 2.1's impact categories.

Figure 8 below shows the normalized results for the three PC cases.

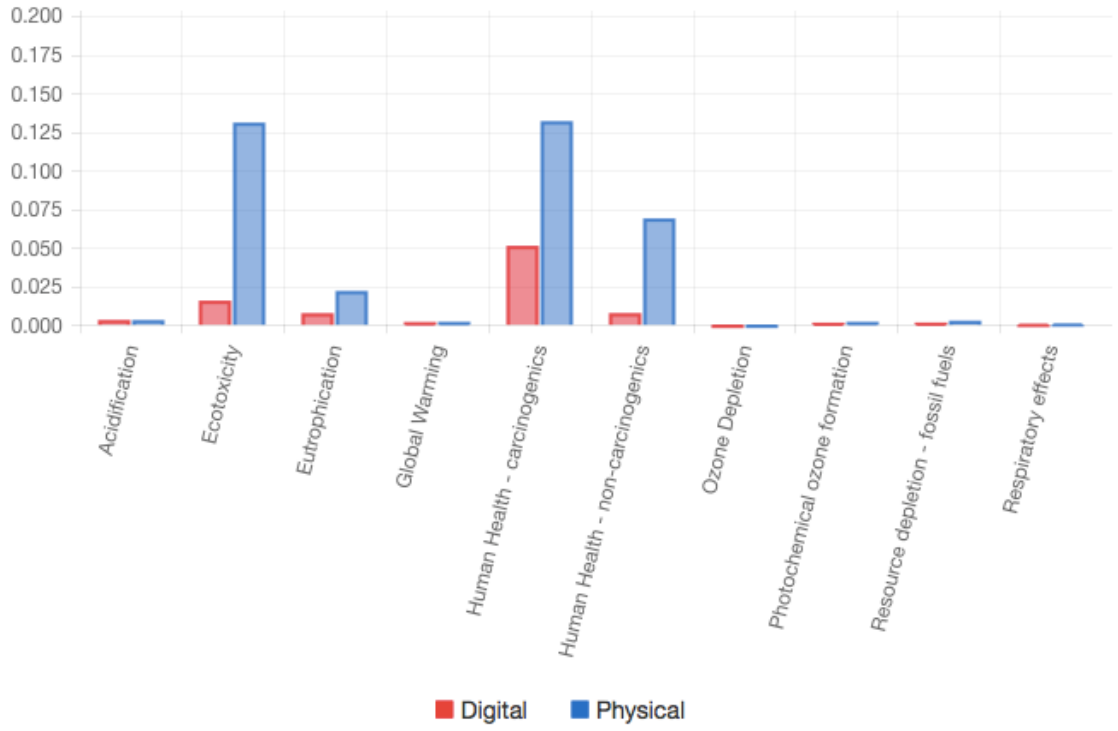

Figure 8. Normalized bar chart for PC (from OpenLCA).

As with the two consoles, carcinogens is the impact category with the most impact for all the cases, though the physical case with the DVD drive equals it in the ecotoxicity category. As before, there are negligible impacts in many other categories, with more moderate impacts in non-carcinogens and eutrophication once the results are normalized.

Sensitivity Analysis Results – Changes to Digital Systems

Sensitivity analysis can be used to test assumptions made during an LCA, or to test the influence of various aspects of a given system. Some changes were made to both the physical and the digital systems in this study. Below, the results of changes to the digital system are explored.

PS3

For PS3, digital distribution results in a smaller footprint than physical distribution in all TRACI 2.1 impact categories, the only platform where one method came out as clearly being less damaging. The first sensitivity analysis case changes digital distribution by increasing internet energy efficiency measured by kWh/GB, as calculated by reduction factors in Weber et. al. This change will only increase digital distribution's favorability from an environmental impact standpoint, and is labeled as SA1 in OpenLCA's charts below.

Similarly, the second sensitivity case for digital systems, labeled SA2 in OpenLCA's charts, brings non-major game titles into the average for file size, which results in a substantial file size reduction. As there is a direct correlation between file size and energy consumed in in data transfer, this also results in digital distribution seeing a considerable reduction in its impacts from the base case. Table 4 below shows the LCIA results of both digital sensitivity cases compared to the base cases for PS3.

Table 4. LCIA results for PS3, base cases and digital sensitivity analyses (from OpenLCA).

Impact category	Digital base	Physical base	SA1	SA2	Unit
Acidification	1.87220e-1	2.04461e-1	1.33818e-1	1.52972e-1	kg SO2 eq
Ecotoxicity	1.19273e+2	1.48187e+2	9.05435e+1	1.00947e+2	CTUe
Eutrophication	1.09871e-1	1.18939e-1	7.95188e-2	9.04237e-2	kg N eq
Global Warming	2.78283e+1	3.22782e+1	1.98661e+1	2.27215e+1	kg CO2 eq
Human Health - carcinogenics	1.75303e-6	2.12166e-6	1.30700e-6	1.46799e-6	CTUh
Human Health - non-carcinogenics	5.42548e-6	6.56110e-6	4.12649e-6	4.59704e-6	CTUh
Ozone Depletion	1.24484e-6	1.99189e-6	8.88156e-7	1.01606e-6	kg CFC-11 eq
Photochemical ozone formation	1.29314e+0	1.58976e+0	9.23626e-1	1.05615e+0	kg O3 eq
Resource depletion - fossil fuels	1.63676e+1	2.44336e+1	1.16832e+1	1.33630e+1	MJ surplus
Respiratory effects	1.14857e-2	1.30053e-2	8.24369e-3	9.40716e-3	kg PM2.5 eq

Of the two, the increase in internet energy efficiency results in a greater change to the impacts of the digital download. Both had the same fundamental effect of reduction, but higher energy efficiency moreso. This comes into clearer light in figure 9, which shows all the normalized results as a comparative bar chart.

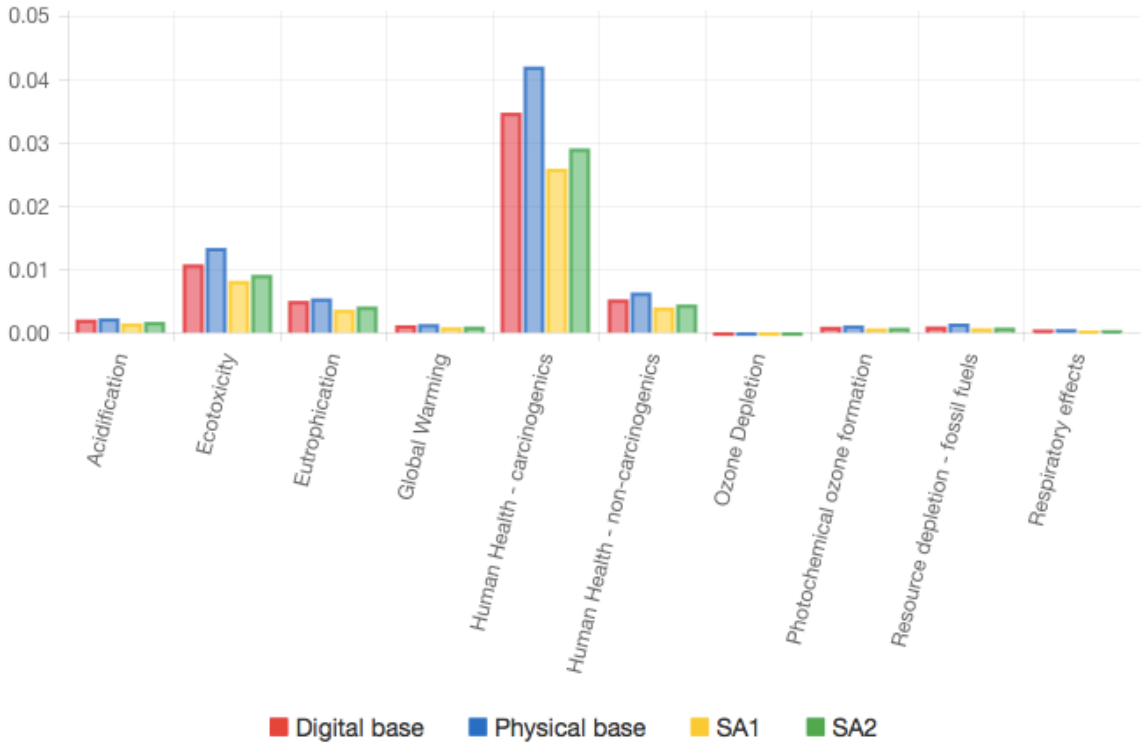

Figure 9. Normalized bar chart for PS3, base cases and digital sensitivity analyses (from OpenLCA).

The impact categories that PS3 games make the greatest contribution to remain the same as all the base cases, with carcinogens being the highest. Impacts are negligible in some categories including ozone depletion and respiratory effects.

PS4

The same set of sensitivity analyses is conducted on the PS4 platform. Table 5 below shows the LCIA results of the PS4 base cases and the digital sensitivity cases. The sensitivity cases are labeled the same as for the PS3 cases.

Table 5. LCIA results for PS4, base cases and digital sensitivity analyses (from OpenLCA).

Impact category	Digital base	Physical base	SA1	SA2	Unit
Acidification	2.25826e-1	1.83441e-1	1.29070e-1	1.69139e-1	kg SO2 eq
Ecotoxicity	1.38434e+2	1.33788e+2	8.63805e+1	1.07896e+2	CTUe
Eutrophication	1.31514e-1	1.06416e-1	7.65202e-2	9.92869e-2	kg N eq
Global Warming	3.35920e+1	2.91584e+1	1.91657e+1	2.51402e+1	kg CO2 eq
Human Health - carcinogenics	2.05905e-6	1.91456e-6	1.25093e-6	1.58518e-6	CTUh
Human Health - non-carcinogenics	6.28901e-6	5.90463e-6	3.93543e-6	4.90819e-6	CTUh
Ozone Depletion	1.50319e-6	1.85243e-6	8.56933e-7	1.12458e-6	kg CFC-11 eq
Photochemical ozone formation	1.56049e+0	1.44470e+0	8.90975e-1	1.16824e+0	kg O3 eq
Resource depletion - fossil fuels	1.97589e+1	2.25989e+1	1.12715e+1	1.47865e+1	MJ surplus
Respiratory effects	1.38192e-2	1.17092e-2	7.94508e-3	1.03774e-2	kg PM2.5 eq

As with before, making data transfer more energy efficient lessens the impacts of digital distribution. The same is true for reducing file size. Both make a mixed comparison entirely favorable for digital distribution. In the base scenarios, physical distribution results in a smaller footprint in all impact categories but two. When data transfer is made more energy efficient and file sizes shrink, digital distribution outperforms physical distribution in all impact categories on the PS4.

Figure 10 shows the normalized results of all PS4 base cases, and the digital sensitivity cases.

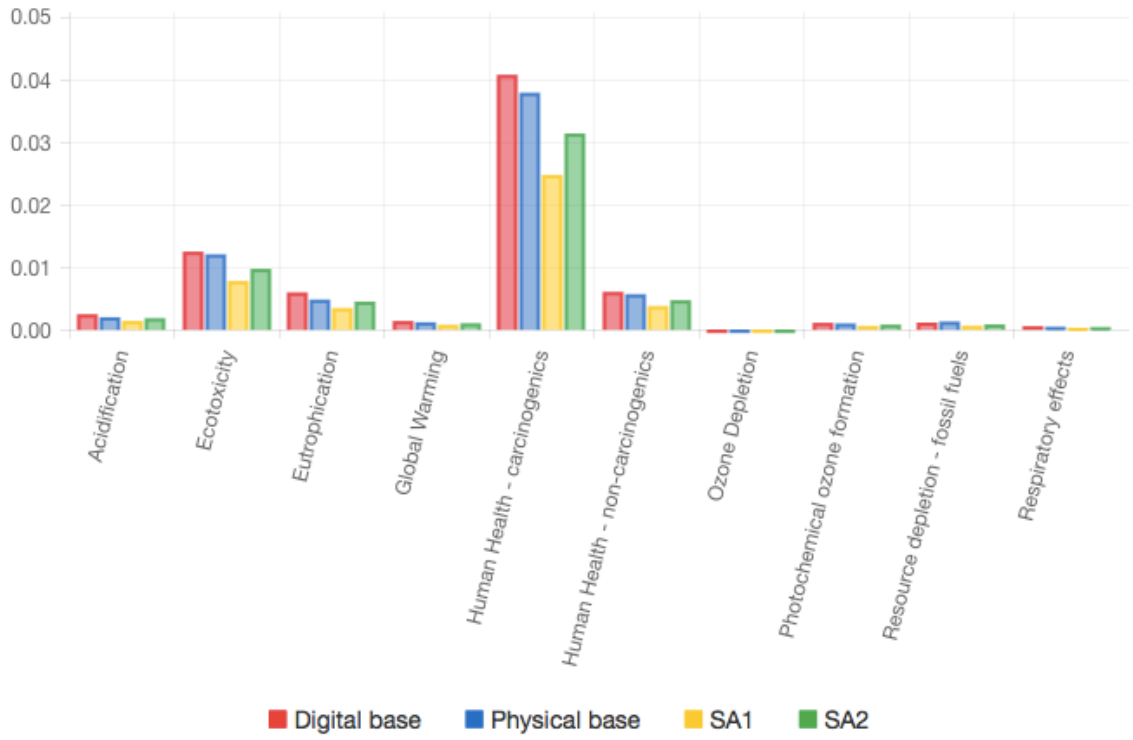

Figure 10. Normalized bar chart for PS4, base cases and digital sensitivity analyses (from OpenLCA).

Like the PS3, on the PS4 the positive effects of smaller file sizes are less than those brought by higher data transfer energy efficiency. However, smaller file sizes are still enough to make digital downloads on PS4 the more environmentally favorable option across all categories. The categories with the highest and lowest impacts generally remain the same. Like with the PS3, PS4 games carry the greatest environmental costs in carcinogen emissions.

PC

The PC platform is more complicated than either of the console cases, because of the DVD drive. Like with the base cases, the sensitivity cases are compared with the DVD drive included and excluded from analysis. Table 6 below shows the LCIA results

for the PC base cases, and both digital sensitivity cases. Labels are the same as in the console cases for the sensitivity analyses.

Table 6. LCIA results for PC, base cases and digital sensitivity analyses (from OpenLCA).

Impact category	Digital	Physical (no DVD drive)	Physical base	SA1	SA2	Unit
Acidification	2.84875e-1	1.52922e-1	2.81956e-1	1.53832e-1	2.08436e-1	kg SO2 eq
Ecotoxicity	1.73121e+2	1.13907e+2	1.45011e+3	1.02623e+2	1.31990e+2	CTUe
Eutrophication	1.65620e-1	8.83763e-2	4.82575e-1	9.11391e-2	1.22173e-1	kg N eq
Global Warming	4.23825e+1	2.49159e+1	4.66527e+1	2.28442e+1	3.09855e+1	kg CO2 eq
Human Health - carcinogenics	2.58204e-6	1.71982e-6	6.66000e-6	1.48755e-6	1.94352e-6	CTUh
Human Health - non-carcinogenics	7.86252e-6	4.98282e-6	7.14217e-5	4.67495e-6	6.00276e-6	CTUh
Ozone Depletion	1.89670e-6	1.69039e-6	4.33967e-6	1.02144e-6	1.38615e-6	kg CFC-11 eq
Photochemical ozone formation	1.96871e+0	1.24552e+0	2.70751e+0	1.06195e+0	1.43978e+0	kg O3 eq
Resource depletion - fossil fuels	2.49299e+1	2.05024e+1	4.58723e+1	1.34349e+1	1.82247e+1	MJ surplus
Respiratory effects	1.74228e-2	1.00309e-2	2.29258e-2	9.46723e-3	1.27821e-2	kg PM2.5 eq

Unlike the console cases, even with higher internet energy efficiency and smaller file sizes, digital distribution is not entirely favorable across all categories compared to physical distribution when the DVD drive is excluded from the system. However, digital distribution outperforms physical without the DVD drive in many categories, though the

results vary between the two sensitivity cases. Physical distribution has a smaller footprint in acidification and eutrophication, along with carcinogens, ozone formation and fossil fuel depletion for the second sensitivity case. The results are also very close though slightly favorable for digital distribution with higher energy efficiency in ecotoxicity, carcinogens, non-carcinogens and respiratory effects with higher internet energy efficiency. With higher internet energy efficiency, digital is more clearly favorable in global warming, ozone depletion, smog formation and fossil fuel depletion. As with the console cases, decreasing file size and increasing energy efficiency both reduced the digital case's footprint, but with more mixed results.

Figure 11 shows the normalized bar chart for PC with all base cases and the digital sensitivity analyses.

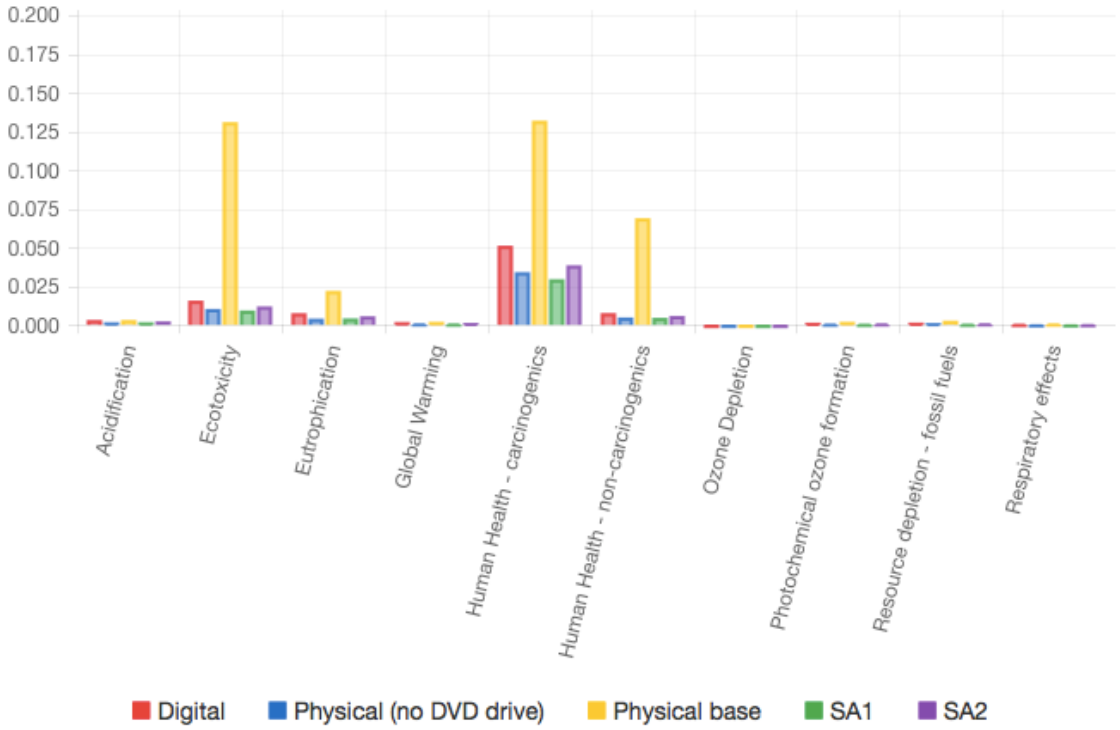

Figure 11. Normalized bar chart for PC, base cases and digital sensitivity analyses (from OpenLCA).

Like with the console cases, PC games show less sensitivity to small file size than to increasing energy efficiency in internet data transfer. Higher energy efficiency makes the digital download option a less environmentally damaging option in most categories compared to a physical game without the DVD drive; smaller file sizes gives it a smaller footprint in only a handful of categories. With smaller file sizes, digital distribution had a lesser impact in only ozone and fossil fuel depletion. It still remained a more damaging option in all other TRACI 2.1 categories with smaller file sizes.

Sensitivity Analysis Results – Changes to Physical Systems

As with the digital systems, some changes were made to the physical cases to test the influence of different aspects of the system on the results. Those are explored below.

PS3

The first change to the physical system is in material that goes into the disc – exchanging aluminum alloy for silver alloy as the metal coating on the bottom of the disc. In OpenLCA's charts below, this analysis is labeled SA3. The second sensitivity case examines the transportation, looking at both higher and lower distances for distribution. These are labeled SA4 upper and SA4 lower, respectively. Table 7 below shows the LCIA results for all the PS3's base cases and the physical sensitivity cases.

Table 7. LCIA results for PS3, base cases and physical sensitivity analyses (from OpenLCA).

Impact category	Digital base	Physical base	SA3	SA4 lower	SA4 upper	Unit
Acidification	1.87412e-1	2.04461e-1	2.07695e-1	1.90745e-1	2.04589e-1	kg SO2 eq
Ecotoxicity	1.19404e+2	1.48187e+2	1.92756e+2	1.30445e+2	1.48249e+2	CTUe
Eutrophication	1.09986e-1	1.18939e-1	1.29080e-1	1.13579e-1	1.18965e-1	kg N eq
Global Warming	2.78569e+1	3.22782e+1	3.24172e+1	2.85123e+1	3.22969e+1	kg CO2 eq
Human Health - carcinogenics	1.75492e-6	2.12166e-6	2.20447e-6	1.88521e-6	2.12281e-6	CTUh
Human Health - non-carcinogenics	5.43148e-6	6.56110e-6	8.91177e-6	5.94124e-6	6.56321e-6	CTUh
Ozone Depletion	1.24611e-6	1.99189e-6	2.00609e-6	1.32161e-6	1.99589e-6	kg CFC-11 eq
Photochemical ozone formation	1.29447e+0	1.58976e+0	1.62266e+0	1.32330e+0	1.59359e+0	kg O3 eq
Resource depletion - fossil fuels	1.63843e+1	2.44336e+1	2.46063e+1	1.75256e+1	2.44716e+1	MJ surplus
Respiratory effects	1.14976e-2	1.30053e-2	1.33136e-2	1.18101e-2	1.30138e-2	kg PM2.5 eq

The effects of the sensitivity analysis on the physical systems did not change the fundamental comparison. Lowering transportation distance results in the lowest emissions for the physical systems, but still not below those for the digital base case. In acidification and smog formation, the digital case and SA4 lower cases come very close, but the digital case still has slightly lower emissions.

In all TRACI 2.1 impact categories, choosing silver alloy over aluminum leads to that case having the highest emissions in all categories. Figure 12 shows the normalization chart, which brings some of these comparisons into clearer light.

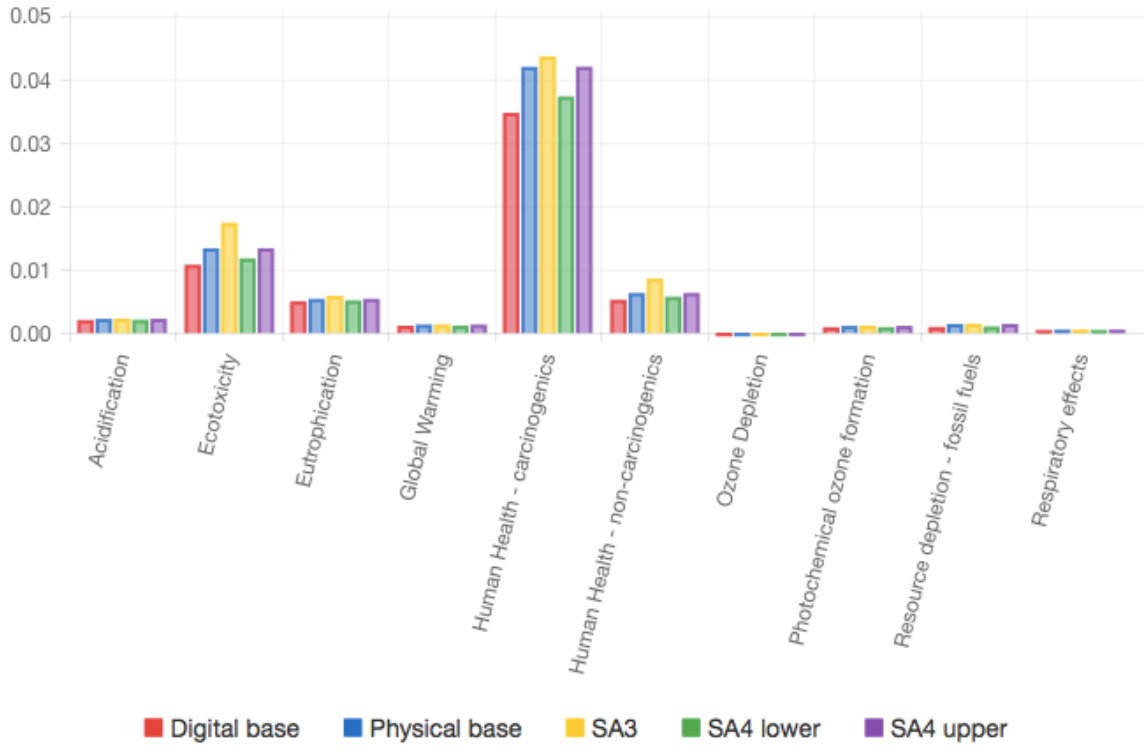

Figure 12. Normalized bar chart for PS3, base cases and physical sensitivity analyses (from OpenLCA).

Carcinogens remains the category with the greatest impacts, with ecotoxicity having the second greatest impacts. In all categories with clear impacts, digital remains the most favorable distribution method on PS3. But overall, the physical case shows greatest sensitivity to silver alloy, and a lowering of the transportation distance.

PS4

The same analyses are conducted on the PS4, along with the same labels in OpenLCA. Table 8 below shows the LCIA results for the PS4 base cases and the physical sensitivity analyses.

Table 8. LCIA results for PS4, base cases and physical sensitivity analyses (from OpenLCA).

Impact category	Digital base	Physical base	SA3	SA4 lower	SA4 upper	Unit
Acidification	2.25826e-1	1.83441e-1	1.86674e-1	1.83372e-1	1.83569e-1	kg SO2 eq
Ecotoxicity	1.38434e+2	1.33788e+2	1.78358e+2	1.33754e+2	1.33851e+2	CTUe
Eutrophication	1.31514e-1	1.06416e-1	1.16557e-1	1.06402e-1	1.06441e-1	kg N eq
Global Warming	3.35920e+1	2.91584e+1	2.92974e+1	2.91483e+1	2.91771e+1	kg CO2 eq
Human Health - carcinogenics	2.05905e-6	1.91456e-6	1.99737e-6	1.91395e-6	1.91570e-6	CTUh
Human Health - non-carcinogenics	6.28901e-6	5.90463e-6	8.25530e-6	5.90350e-6	5.90674e-6	CTUh
Ozone Depletion	1.50319e-6	1.85243e-6	1.86663e-6	1.85029e-6	1.85643e-6	kg CFC-11 eq
Photochemical ozone formation	1.56049e+0	1.44470e+0	1.47760e+0	1.44265e+0	1.44853e+0	kg O3 eq
Resource depletion - fossil fuels	1.97589e+1	2.25989e+1	2.27717e+1	2.25785e+1	2.26369e+1	MJ surplus
Respiratory effects	1.38192e-2	1.17092e-2	1.20176e-2	1.17046e-2	1.17178e-2	kg PM2.5 eq

On the PS4, physical sensitivity analysis results are more mixed than on the PS3. Overall, physical distribution still results in lower emissions in most categories compared to digital distribution. Digital remains favorable in only two categories – ozone and fossil fuel depletion, the same categories when only comparing the base cases. Both the higher and lower transportation distances result in lower emissions in all categories except for those two. Figure 13, a normalized bar chart of all these cases, makes this clearer.

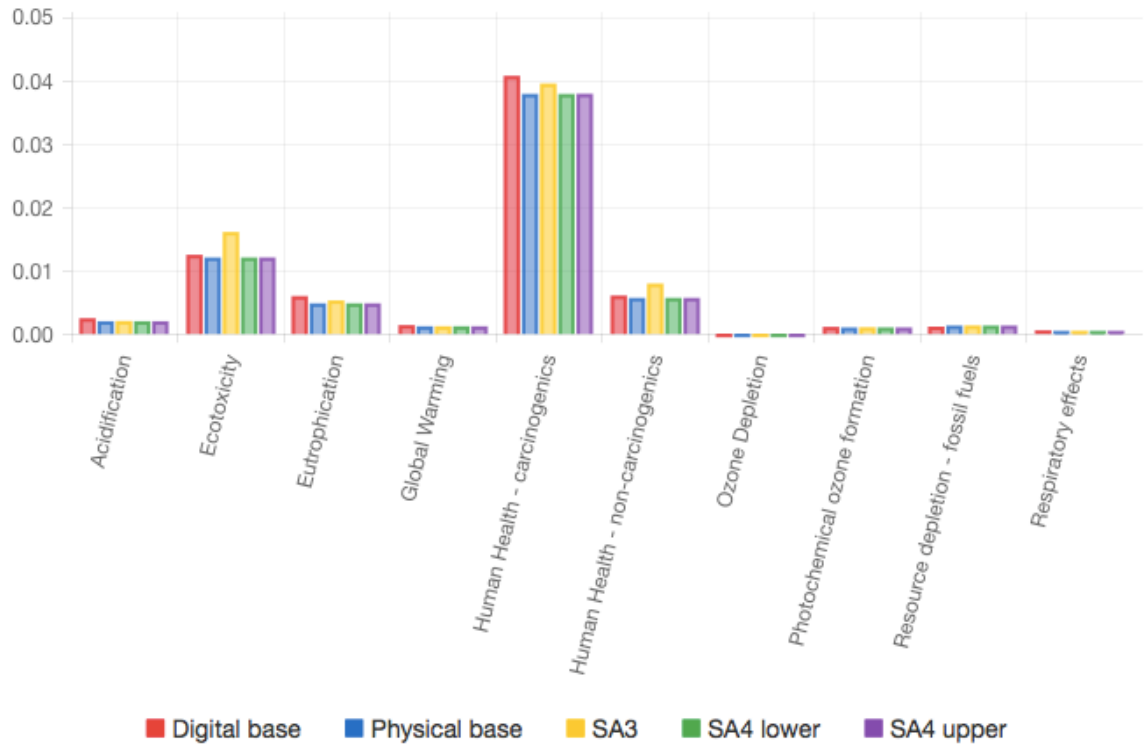

Figure 13. Normalized bar chart for PS4, base cases and physical sensitivity analyses (from OpenLCA).

However, silver alloy did overtake the digital base in emissions in two categories, ecotoxicity and non-carcinogens. This bar chart shows this clearly. Overall, the PS4's physical system shows more sensitivity to silver alloy than either increasing or decreasing the distribution distance. The fundamental comparison remains the same as to the base cases, with mixed results. Digital distribution results in less emissions in some categories, but more in others.

PC

The same sensitivity analyses are conducted on the PC platform, which has the same additional factor as before – the DVD drive. Thus, the sensitivity analysis on the PC physical system is conducted with and without the DVD drive, separately. All cases

are compared to the base cases. Table 9 below looks at the PC digital base case, and compares it to the physical base case, and its sensitivity analyses, but all with the DVD drive included. Labels are the same as for the console cases.

Table 9. LCIA results for PC, base cases and physical sensitivity analyses (from OpenLCA).

Impact category	Digital	Physical	SA3	SA4 lower	SA4 upper	Unit
Acidification	2.84875e-1	2.81956e-1	3.50272e-1	2.80526e-1	2.84621e-1	kg SO2 eq
Ecotoxicity	1.73121e+2	1.45011e+3	2.61121e+3	1.44941e+3	1.45142e+3	CTUe
Eutrophication	1.65620e-1	4.82575e-1	6.59406e-1	4.82295e-1	4.83098e-1	kg N eq
Global Warming	4.23825e+1	4.66527e+1	3.74559e+1	4.64445e+1	4.70409e+1	kg CO2 eq
Human Health - carcinogenics	2.58204e-6	6.66000e-6	6.70659e-6	6.64728e-6	6.68370e-6	CTUh
Human Health - non-carcinogenics	7.86252e-6	7.14217e-5	1.36333e-4	7.13982e-5	7.14654e-5	CTUh
Ozone Depletion	1.89670e-6	4.33967e-6	3.23777e-6	4.29521e-6	4.42255e-6	kg CFC-11 eq
Photochemical ozone formation	1.96871e+0	2.70751e+0	3.38457e+0	2.66492e+0	2.78690e+0	kg O3 eq
Resource depletion - fossil fuels	2.49299e+1	4.58723e+1	3.87268e+1	4.54494e+1	4.66607e+1	MJ surplus
Respiratory effects	1.74228e-2	2.29258e-2	2.88469e-2	2.28306e-2	2.31033e-2	kg PM2.5 eq

With the DVD drive included, digital overwhelmingly outperforms physical distribution. One category where this is not the case is acidification, with the physical base case and lower distance transportation case both having slightly lower emissions than digital distribution. The digital and higher transportation physical cases have approximately equal emissions in this category. The other category in which digital is

not the lowest emission case is global warming, where the physical case with silver alloy has lower emissions. It is also lower than all the other physical cases. Silver alloy also results in lower emissions than the physical base case and transportation sensitivity cases in ozone and fossil fuel depletion.

The normalized results below in figure 14 make these comparisons somewhat clearer.

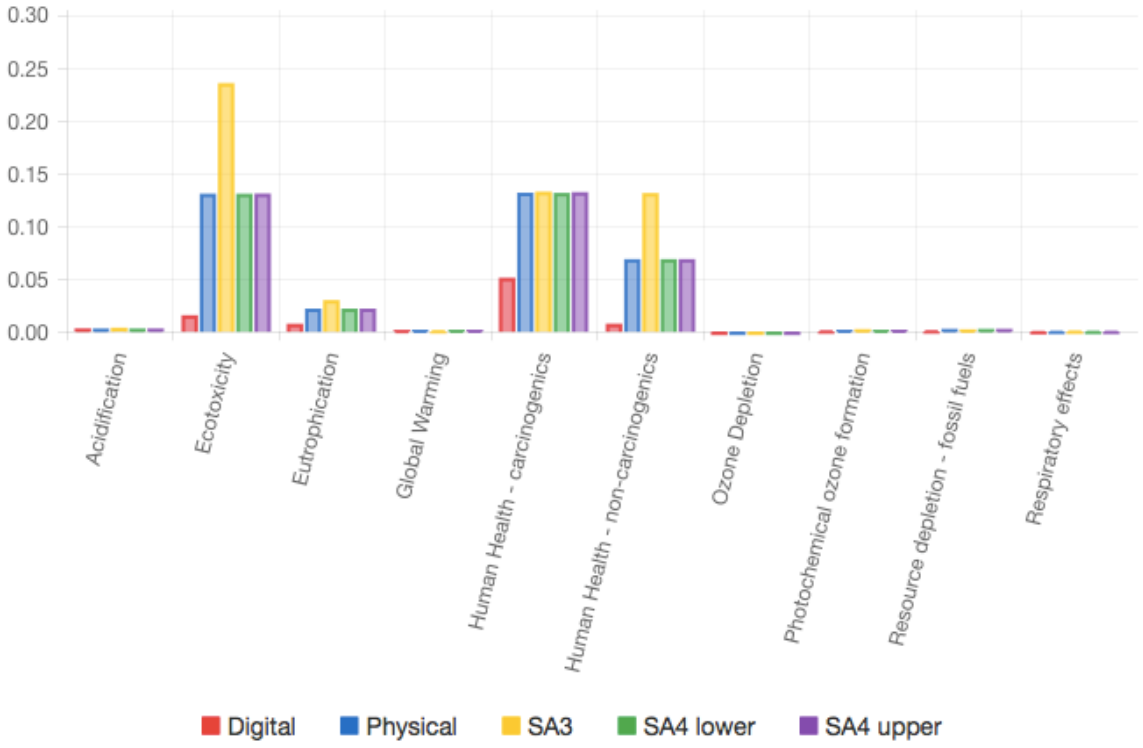

Figure 14. Normalized bar chart for PC, digital and physical cases with DVD drive (from OpenLCA).

In this case, the category with the greatest impacts becomes ecotoxicity in the case of the silver alloy. Carcinogens is also high across all cases, with non-carcinogens also having considerable impacts. Most other categories have lower emissions factors across all cases.

However, the results change when the DVD drive is removed from the physical cases. Table 10 looks at LCIA results for all the same cases, except with the DVD drive excluded.

Table 10. LCIA results for PC, base cases and physical sensitivity analyses without DVD drive (from OpenLCA).

Impact category	Digital	Physical	SA3	SA4 lower	SA4 upper	Unit
Acidification	2.84875e-1	1.52922e-1	2.42636e-1	1.52801e-1	1.53149e-1	kg SO2 eq
Ecotoxicity	1.73121e+2	1.13907e+2	1.35184e+3	1.13848e+2	1.14018e+2	CTUe
Eutrophication	1.65620e-1	8.83763e-2	3.69919e-1	8.83524e-2	8.84207e-2	kg N eq
Global Warming	4.23825e+1	2.49159e+1	2.87462e+1	2.48982e+1	2.49489e+1	kg CO2 eq
Human Health - carcinogenics	2.58204e-6	1.71982e-6	4.01835e-6	1.71874e-6	1.72184e-6	CTUh
Human Health - non-carcinogenics	7.86252e-6	4.98282e-6	7.02744e-5	4.98082e-6	4.98654e-6	CTUh
Ozone Depletion	1.89670e-6	1.69039e-6	2.06671e-6	1.68661e-6	1.69744e-6	kg CFC-11 eq
Photochemical ozone formation	1.96871e+0	1.24552e+0	2.15811e+0	1.24190e+0	1.25227e+0	kg O3 eq
Resource depletion - fossil fuels	2.49299e+1	2.05024e+1	2.52549e+1	2.04665e+1	2.05695e+1	MJ surplus
Respiratory effects	1.74228e-2	1.00309e-2	1.85854e-2	1.00228e-2	1.00460e-2	kg PM2.5 eq

The results become much more even across the TRACI 2.1 impact categories, but physical distribution generally outperforms digital. Digital distribution has the highest

impacts in some categories, such as acidification and global warming. The third sensitivity analysis case, silver alloy instead of aluminum on the discs, has the highest emissions in ecotoxicity, eutrophication, carcinogens, non-carcinogens, ozone depletion, respiratory effects and fossil fuel depletion. Silver alloy, in the PC case, becomes a very unfavorable option, greatly increasing emissions across these categories. However, the physical base case and both the higher and lower distance cases result in lower emissions than digital and the silver alloy cases. Some of these comparisons are clearer in Figure 15, showing the normalized bar chart.

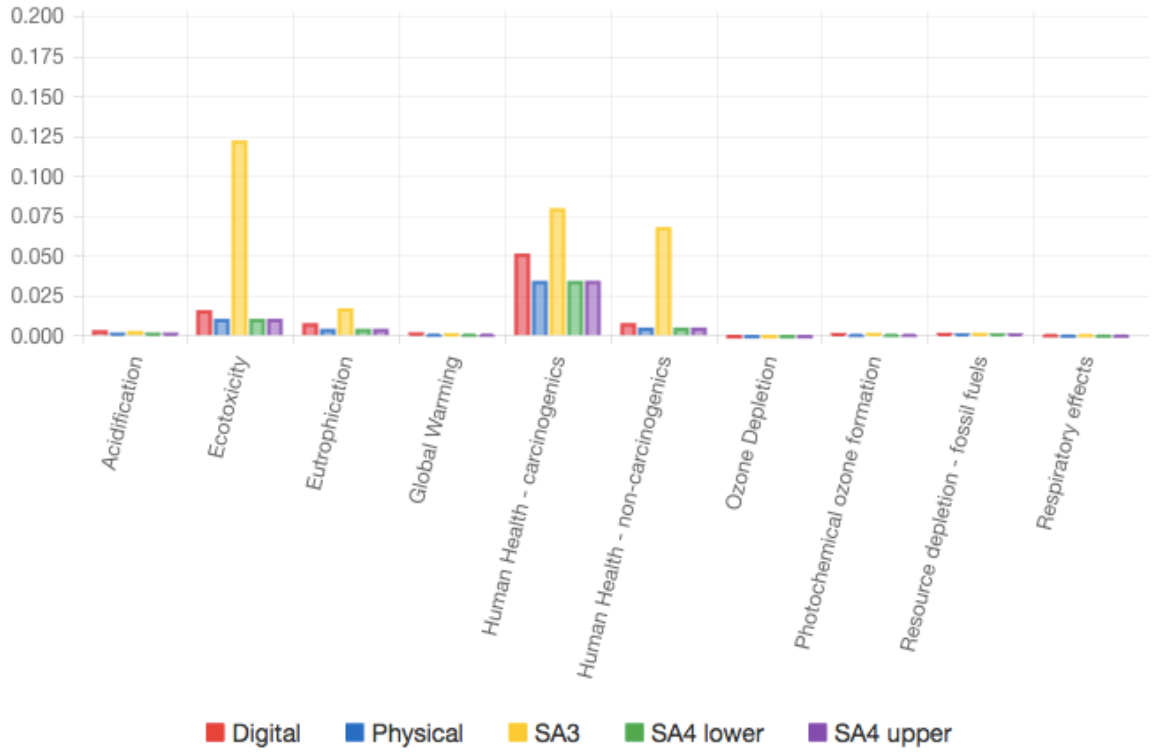

Figure 15. Normalized bar chart for PC, base cases and physical sensitivity analyses without DVD drive (from OpenLCA).

The categories with high emissions are carcinogens, ecotoxicty (for the silver alloy case) and non-carcinogens (also for the silver alloy case). The other categories have lower emission footprints.

Chapter IV

Discussion

The overall results are mixed. Whether digital or physical distribution results in lower emissions depends on both a consumer's gaming platform and the impact category of concern in the TRACI 2.1 framework. The only exception to that is for the PS3, where digital distribution results in lower emissions across all categories in the base case, both digital sensitivity analysis cases, and both physical sensitivity analysis cases. The caveat to that is that the PS3, as of this writing, is last-generation gaming hardware and its use is likely to decline over time among consumers. The PC and PS4 are more current systems and are more likely to see steady or increasing adoption in the near future as gaming platforms, alongside other current-generation consoles such as the Xbox One. The results for these systems may be more meaningful for the future and to the current state of the gaming market.

Overall results

For the PS4, base case measurements are somewhat mixed, but physical distribution results in lower emissions in most categories compared to the PS3. This is due to higher energy demands for PS4 downloads compared to the PS3, due simply to larger files sizes and a more energy intensive system on average. The energy demand in the download process is the primary difference between the two consoles' respective

download processes. As previously discussed and demonstrated, for digital downloads, there is a direct positive relationship between file size and energy consumption. Larger file sizes require more energy to transfer. This pushes the download footprint of the PS4.

Largely the same can be said for the PC platform, which boasts the highest average file size. Even with larger manufacturing burdens associated with physical PC games due to DVDs being favored over Blu-ray discs, the physical footprint is smaller than the digital footprint across all TRACI 2.1 categories – at least once the DVD drive is disassociated from the system.

The sensitivity analyses, particularly on the digital systems, may present a more realistic picture of where gaming and digital distribution are now and where it may be headed. As previously stated, the base case digital analyses use the most recently available measured numbers for energy consumed in data transfer. These numbers are from 2010 – six years prior to this writing. A sensitivity analysis conducted on the digital systems estimated current numbers based on established research, which had a net effect of drastically reducing energy consumption in download. This sensitivity case further shrinks the PS3's digital footprint. On PS4, it makes an unfavorable comparison for downloads entirely favorable, reducing the digital footprint below the physical footprint. On PC it makes an unfavorable comparison more mixed, with digital downloads having a smaller footprint in some categories but not others. But it reduces the digital system's footprint considerably.

Smaller file sizes have a similar, if less magnified, effect on the digital system. As stated previously, many downloaded games are smaller independent titles that do not see physical releases. So while the base case only includes major release titles, for digital

systems, it is important to consider the effect of these smaller games. This brings down the file size, and with it, the energy consumed to download games. On PS3, this made the smaller comparative footprint for digital distribution more so. On PS4, considering these smaller downloads brings the base case mixed comparison into one where downloads outperformed optical discs. On PC, the results are similar to increasing energy efficiency of downloading – downloads performed better, though still with a few TRACI 2.1 categories where a physical disc generates fewer emissions. However, in the current market for digital distribution, the most realistic scenario may be to account for smaller file sizes and less energy intensive data transmission at once. If both are done in tandem in an assessment on PC games, it may make mixed results favorable for downloading. This scenario is beyond the scope of this study.

The physical sensitivity analyses also had mixed results – except on the PS3. All physical sensitivity cases still resulted in a larger environmental footprint than the digital base case. On last generation gaming hardware, digital distribution is the lower-impact choice.

On more current hardware the results remain mixed, like the base case comparisons. For PS4, physical distribution generally results in a smaller footprint, even when using silver alloy instead of aluminum and transporting a game for a longer distance. On PC, the sensitivity analyses done on the physical system still results in a smaller footprint than digital distribution – except for when the DVD drive is part of the system.

Overall, the distribution of video games showed that the highest sensitivity is in the digital systems, with both energy efficiency of data transfer and file size greatly

affecting the system – and the comparison. On PC, the physical system shows great sensitivity to the DVD drive, a piece of hardware necessary for gaming with physical media but outside the games themselves. This indicates that gaming's greatest impacts may not be in games themselves but in the hardware required to play them, regardless of a consumer's chosen platform.

Digital Distribution and the Future

It was stated early on in this paper that most gaming consumers think that digital distribution is likely where gaming is headed. It is already the dominant marketplace on PC, and is growing on consoles and the industry overall. From these analyses, two different forces are the major factors in how large a digital ecosystem's environmental impacts will be – efficiency of data transfer and file sizes. Previous research from Weber et. al. has found that energy efficiency of data transfer increases over time. Their calculation is used in this paper for the first digital sensitivity case. However, as shown previously, file sizes, particularly for big releases, tend to increase over time, and saw a large spike in 2013 and 2014 when the new console generation started. These two competing forces are likely to drive the footprint of the digital distribution ecosystem. This analysis shows that the digital ecosystem is more sensitive to increasing energy efficiency than file size. As of this writing, gaming is about three years into the 8th generation. Going forward, these two forces will be pulling in opposite directions on the digital ecosystem's footprint as it continues to grow within the gaming industry as a whole.

Summary and Conclusions

Digital distribution has been found to have a positive effect on the environmental impact of most forms of media. Streaming movies, downloading music and reading eBooks all have lower environmental impacts when compared to their physical counterparts, at least according to the current body of research. With video games, digital distribution's comparison to physical distribution is mixed. But future developments, such as increases in energy efficiency of data transfer, could stand to make digital distribution a more environmentally favorable option. The results of the more energy efficient system discussed in this paper points towards that conclusion. Future work in this field could benefit from examining file sizes more closely on gaming networks, and could be combined with studies of consumer buying habits to more accurately predict what people buy physically and what they download. This could be especially important on consoles. Future work would also benefit from a better understanding of the energy consumption of the internet, and approximately how much energy data transfer consumes. Digital download ecosystems showed great sensitivity to energy efficiency of data transfer than just file size.

Methodological Changes

Easily the largest change I made to my systems as I got further into the project is how I treated the PC physical system. I initially intended to only include the DVD drive. But as I talked about my research with others and gave it more thought, I realized that while I had reasons to include it, there are equally compelling reasons to exclude it. All of this was previously discussed. This change in my thought process led to me doing two

separate analyses of the PC physical system, one with the DVD drive included and one without it. The physical sensitivity cases for PC are also conducted with this dichotomy.

Another issue I quickly ran into while I was still building my LCA systems was how to account for energy consumption in use. While my experimental data was useful and formed the backbone of that step, I did have to take into account hardware iterations for both console cases, and the great hardware variability of PC, and how these might affect energy consumption. While it took me some weeks of reading, researching and thinking about how to tackle this challenge and what method to use to reasonably estimate average energy consumption in use, it was ultimately a very rewarding problem to solve and led to what I think is a more solid, or at least applicable, study.

Estimating average file size, both for the base case analyses and the sensitivity case, was also a challenge that took some time to consider, think through and implement. But like the energy consumption during gameplay, taking the time to solve this problem led a stronger study due to better understanding the influence the single factor of download file size has on the overall system.

What I Learned and How I Applied It in a Buying Choice

As a consumer of video games on PC, current-generation consoles, last-generation consoles and also handheld consoles, the research done here has and will continue to influence my buying choices as a gamer. Since I do play games on a variety of platforms, spend much of my free time gaming, and buy games fairly frequently I learned that my buying choices could add up to a considerable difference in my personal impact on the environment.

A few weeks prior to this writing, I decided to purchase a recent release exclusively for the PS4, *Ratchet & Clank,* a reimagining and remake of a game from 2002. The original game is one of my favorites from its generation. I had the choice of downloading it from the Playstation Store or visiting our nearest store to buy it, a GameStop located in Waltham, Massachusetts. While making the decision of how to buy the game, I took the environmental impact of my choice into account. During my decision-making, I looked up the game's file size to get a sense of the potential energy cost to download it. As the game measured at 24.4 GB, I knew that the energy cost would be fairly high in the background (Ratchet & Clank, 2016). At that point, having gotten far enough in this research to know the general comparison of digital and physical distribution of games on PS4, I ultimately decided to travel to GameStop and purchase the game there. However, at that time I had not yet conducted the sensitivity analysis with higher energy efficiency. While my decision was also influenced by other factors, such as wishing to exchange games that I was done with for store credit, which I put towards the new game I wanted, the environmental considerations based on this research I had done to that point was a consideration in the decision I made.

Now that I have done all the research, what I now know is likely to change my buying behavior for video games. Even though my most recent purchase for PS4 was on a disc, when I consider the sensitivity results of the digital systems, I may be more compelled to download games on that console, even with some disadvantages to doing so, such as higher prices shortly after launch compared to discs, and inability to lend to friends. If I do buy any more PS3 games, I am much more likely to download them. On PC, I will continue to download games, given the prevalence of smaller titles on the PC

platform and my gaming PC not having a DVD drive built in. On my handhelds, I am also likely to shift more to downloading. I already download most games on my Playstation Vita, but on my Nintendo 3DS I still mostly purchase cartridges, primarily for lending among many friends who also have a 3DS. On that platform price parity is less of an issue, as physical Nintendo games tend to not drop in price as quickly as others, even when used and years after release. These forces may start pushing me to download more on that platform.

As a consumer of games across multiple platforms, I think overall forces in the industry are gradually pushing distribution towards downloading. It is already largely there on PC and growing in the industry overall. To lessen the footprint on downloadable media like games, it may be imperative to focus on energy efficiency in our internet infrastructure. This may be especially true for games, as file sizes are likely to keep increasing if historic trends in the industry continue. If energy efficiency is focused on, downloadable games may generally be a more environmentally friendly choice. But at least on consoles, other issues may need some work to make downloads more enticing to consumers. Chief among them are price parity after launch, and post-launch server support, especially for games with an online component.

LCA shows that to reduce environmental impacts of human activities, all the background activities that go into delivering goods to people have to be considered. This is as true for video games as any other consumable good, particularly the power-intensive digital distribution ecosystem.

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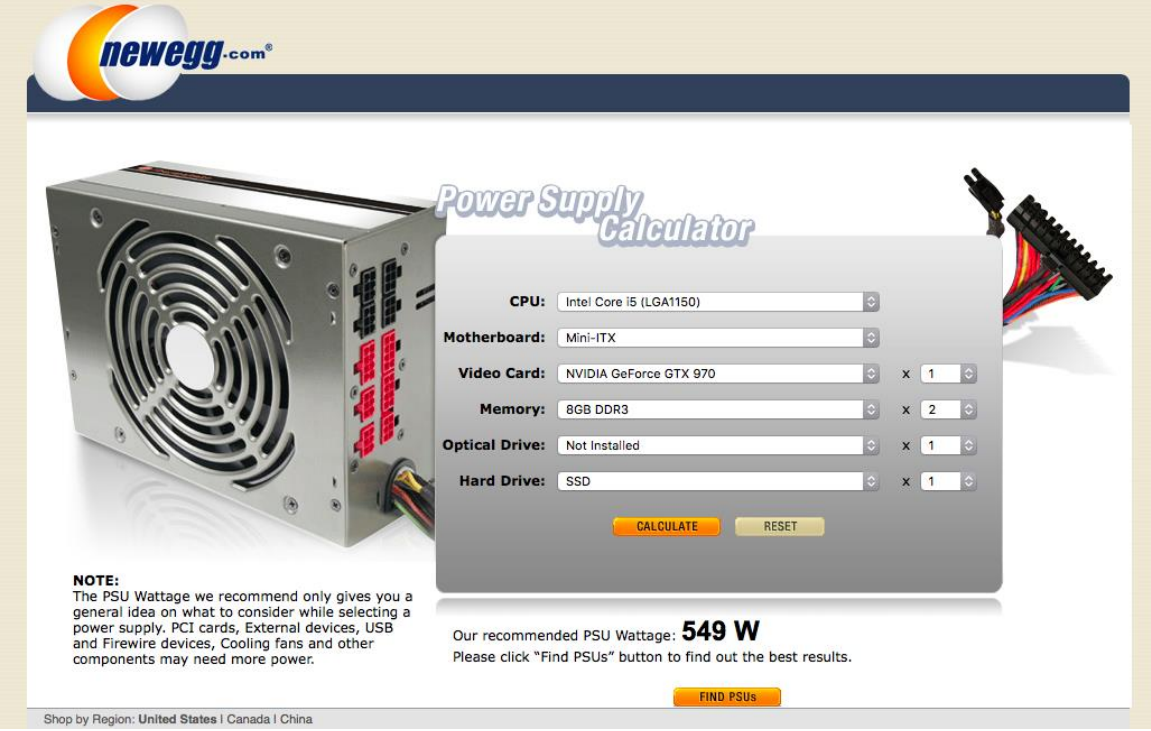
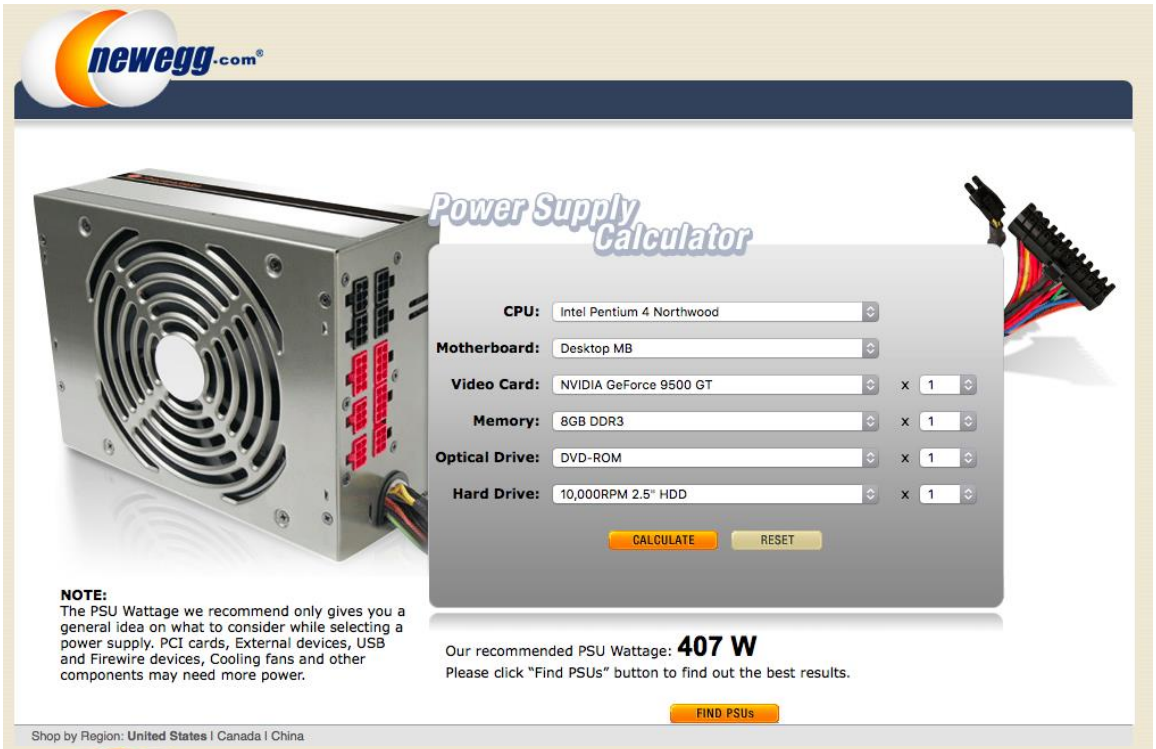
Annex 1

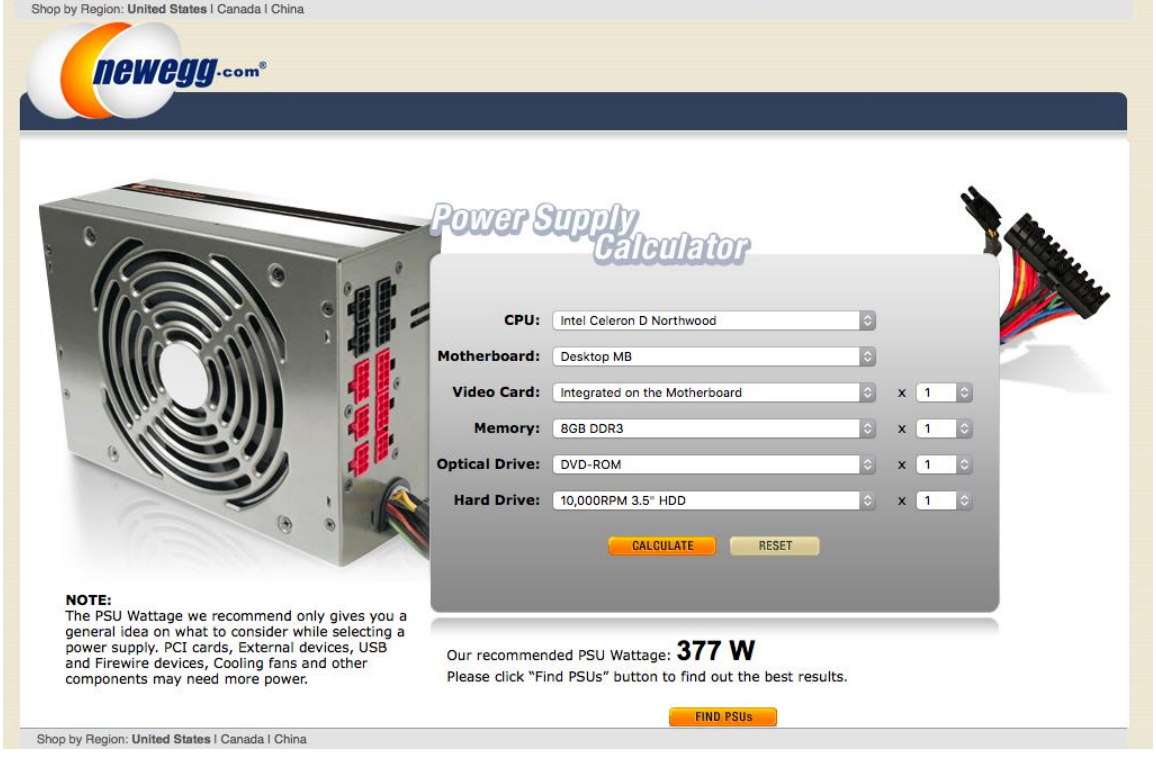
Gaming PC Screenshots from Newegg Calculator

The screenshots shown below are all taken from the PC power calculator on Newegg.com. These were taken to estimate reasonable average energy consumption for PC gameplay, based on a small sample of hardware setups at low, high and medium power ranges. As described in the main text, PC hardware can vary greatly, and Newegg's calculator helps PC builders decide what power supply their machine will need to run to its theoretical maximum. The hardware specifications of an individual machine can influence its power consumption in use.

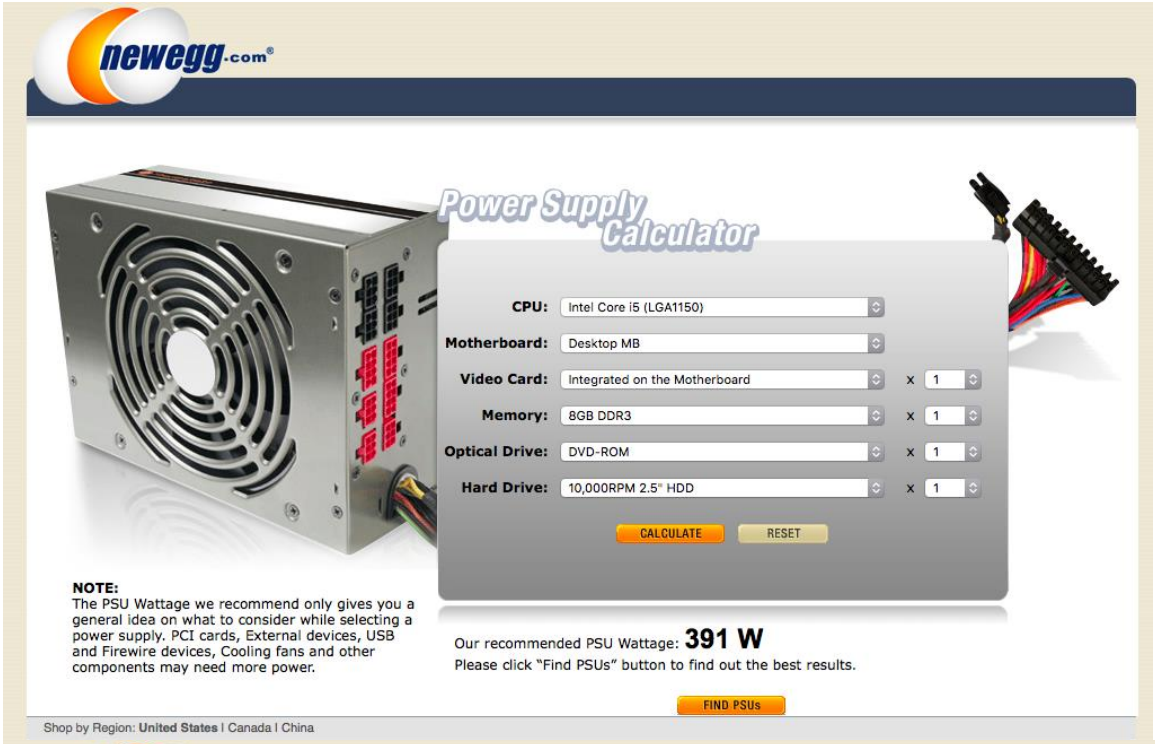


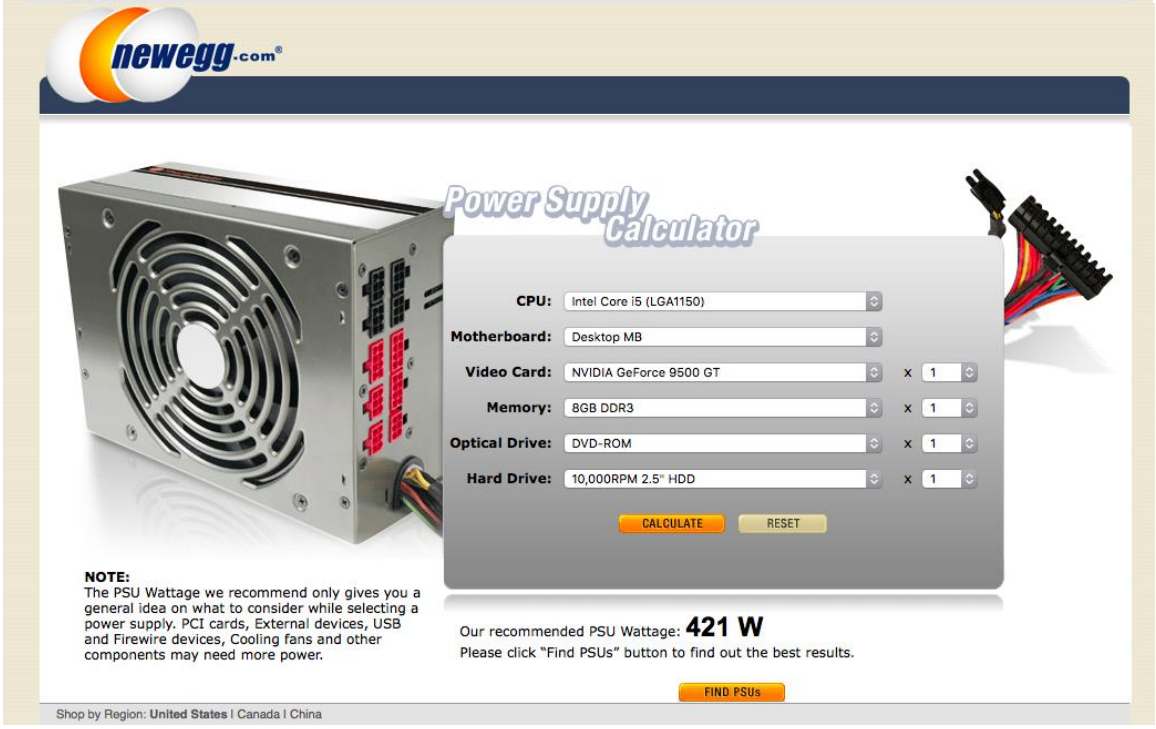
This screenshot above shows the hardware specifications of the PC used for the experimental data gathering. Below are screenshots of other hardware setups for PC, generally based on data available from Valve in their February 2016 Steam Hardware and Software survey. Some setups were also calculated based on the most powerful hardware available to consumers at the time, but not yet used by most Steam users due to the high initial cost of top-of-the-line hardware.

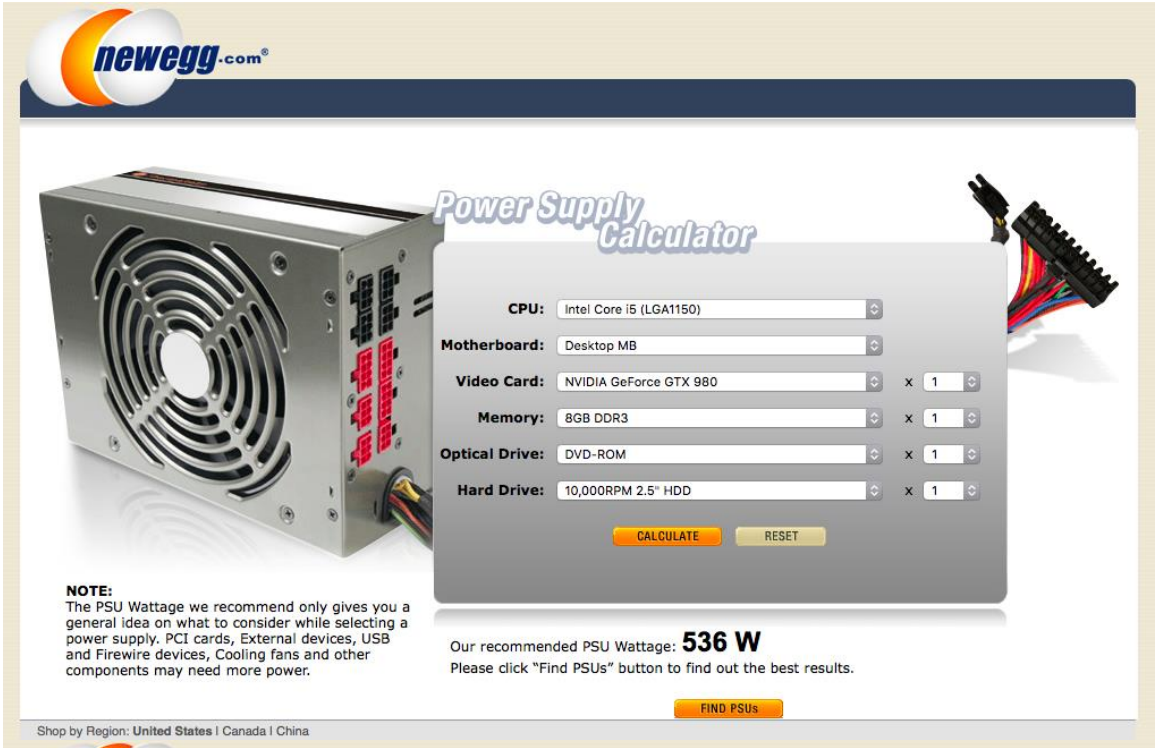

newegg.com
Power Supply Calculator
CPU: Intel Pentium 4 Northwood
Motherboard: Desktop MB
Video Card: NVIDIA GeForce 9500 GT x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 2.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 407 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States I Canada I China

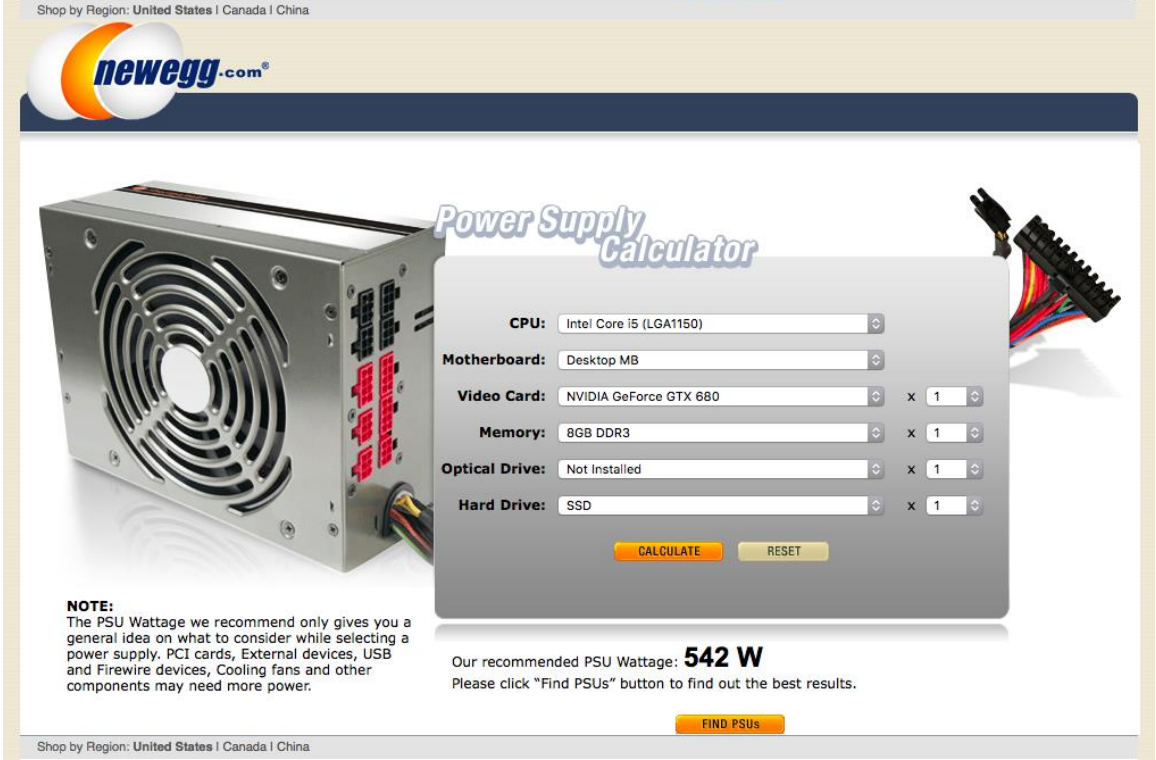

newegg.com
Power Supply Calculator
CPU: Intel Celeron D Northwood
Motherboard: Desktop MB
Video Card: Integrated on the Motherboard x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 3.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 377 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States I Canada I China


newegg.com
Power Supply Calculator
CPU: Intel Celeron D Northwood
Motherboard: Desktop MB
Video Card: NVIDIA GeForce 9500 GT x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 3.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 407 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China
newegg.com
Power Supply Calculator
CPU: Intel Pentium 4 Northwood
Motherboard: Desktop MB
Video Card: Integrated on the Motherboard x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 2.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 377 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


newegg.com
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Desktop MB
Video Card: Integrated on the Motherboard x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 2.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 391 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


newegg.com
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Desktop MB
Video Card: NVIDIA GeForce 9500 GT x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 2.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 421 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China

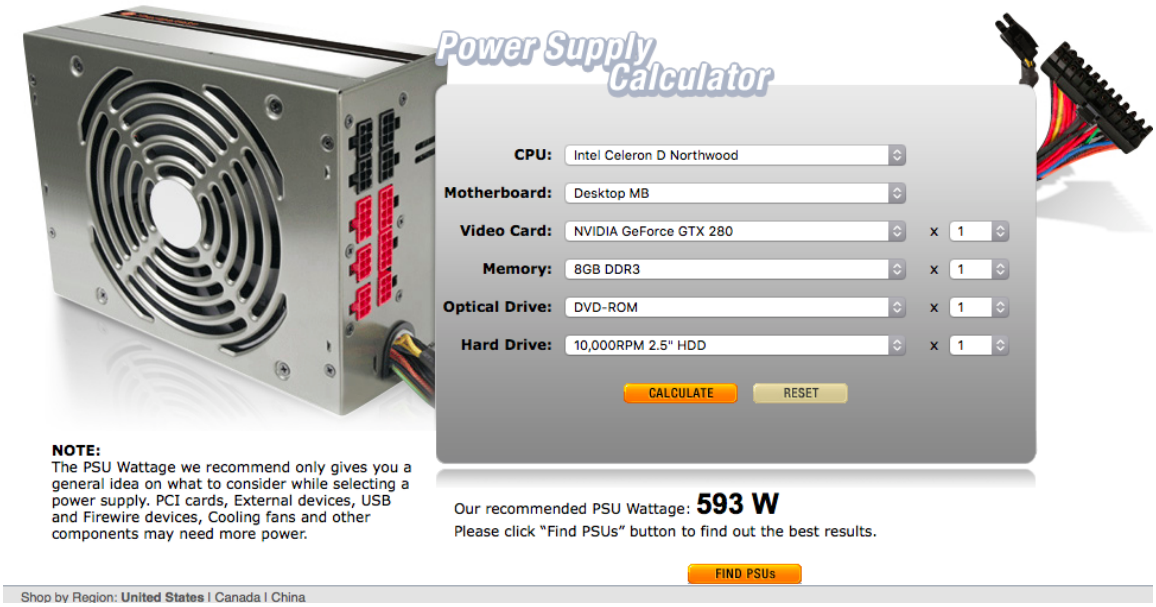

newegg.com
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Desktop MB
Video Card: NVIDIA GeForce GTX 980 x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 2.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 536 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


newegg.com
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Desktop MB
Video Card: NVIDIA GeForce GTX 680 x 1
Memory: 8GB DDR3 x 1
Optical Drive: Not Installed x 1
Hard Drive: SSD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 542 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


newegg.com
Homepage
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Mini-ITX
Video Card: NVIDIA GeForce GTX 680 x 1
Memory: 8GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: SSD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 461 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


newegg.com
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Mini-ITX
Video Card: NVIDIA GeForce GTX 980 Ti x 1
Memory: 8GB DDR3 x 2
Optical Drive: DVD-ROM x 1
Hard Drive: SSD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 518 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


newegg.com
Power Supply Calculator
CPU: Intel Celeron D Northwood
Motherboard: Desktop MB
Video Card: Integrated on the Motherboard x 1
Memory: 4GB DDR3 x 1
Optical Drive: DVD-ROM x 1
Hard Drive: 10,000RPM 2.5" HDD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 376 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China
newegg.com
Power Supply Calculator
CPU: Intel Core i5 (LGA1150)
Motherboard: Desktop MB
Video Card: NVIDIA GeForce GTX 980 Ti x 1
Memory: 8GB DDR3 x 2
Optical Drive: DVD-ROM x 1
Hard Drive: SSD x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 618 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China


Power Supply Calculator
CPU:
Intel Celeron D Northwood
Motherboard:
Desktop MB
Video Card:
NVIDIA GeForce GTX 280
x 1
Memory:
8GB DDR3
x 1
Optical Drive:
DVD-ROM
x 1
Hard Drive:
10,000RPM 2.5" HDD
x 1
CALCULATE
RESET
NOTE:
The PSU Wattage we recommend only gives you a general idea on what to consider while selecting a power supply. PCI cards, External devices, USB and Firewire devices, Cooling fans and other components may need more power.
Our recommended PSU Wattage: 593 W
Please click "Find PSUs" button to find out the best results.
FIND PSUs
Shop by Region: United States | Canada | China

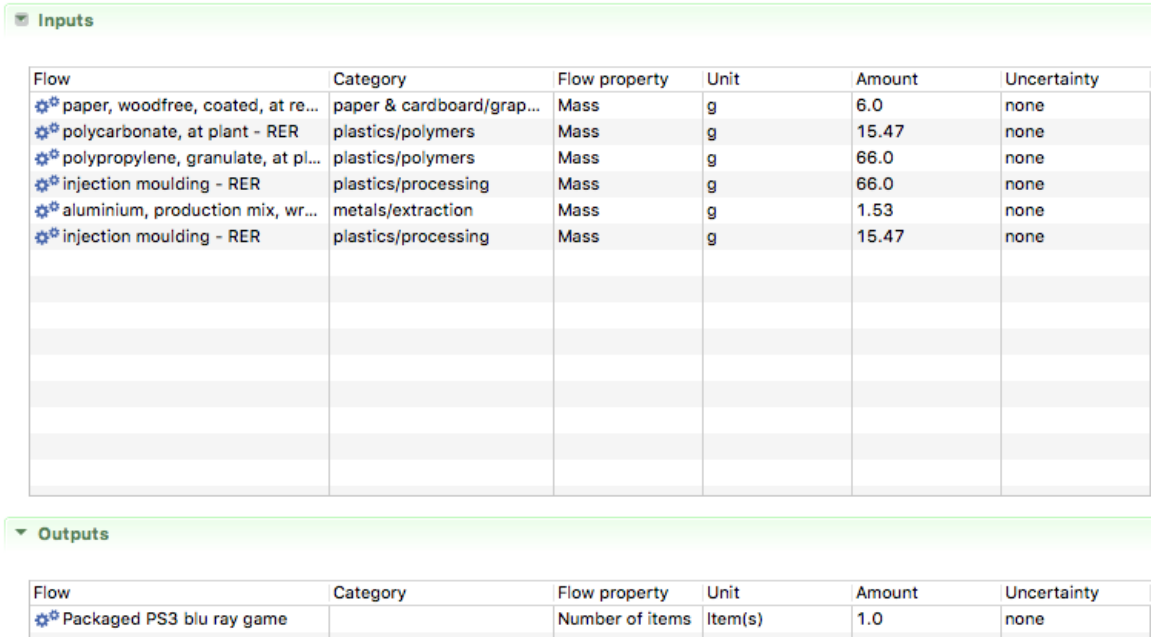
Annex 2

Inputs and Outputs in the Life Cycle Systems

The screenshots shown below were all taken from the input-output screens of OpenLCA for each LCA system. For the physical systems, they are shown, from top to bottom, manufacture-transportation-use. For digital systems, they are shown top to bottom, download-use. Sensitivity cases only show screenshots for the processes that were different from the base case.

Physical Base Cases

PS3



Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none
polycarbonate, at plant - RER	plastics/polymers	Mass	g	15.47	none
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
injection moulding - RER	plastics/processing	Mass	g	66.0	none
aluminium, production mix, wr...	metals/extraction	Mass	g	1.53	none
injection moulding - RER	plastics/processing	Mass	g	15.47	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS3 blu ray game		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.089*1825	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
Packaged PS3 blu ray game		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 blu ray game to consumer		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 blu ray game to consumer		Number of items	Item(s)	1.0	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	33.0368	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 blu ray gameplay		Duration	h	232.0	none

PS4

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
polycarbonate, at plant - RER	plastics/polymers	Mass	g	15.47	none
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
injection moulding - RER	plastics/processing	Mass	g	15.47	none
aluminium, production mix, wr...	metals/extraction	Mass	g	1.53	none
injection moulding - RER	plastics/processing	Mass	g	66.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS4 blu ray		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS4 blu ray		Number of items	Item(s)	1.0	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.089*1825	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 blu ray to consumer		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 blu ray to consumer		Number of items	Item(s)	1.0	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	29.3712	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 blu ray gameplay		Duration	h	232.0	none

PC with DVD drive

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
polycarbonate, at plant - RER	plastics/polymers	Mass	g	42.5	none
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
injection moulding - RER	plastics/processing	Mass	g	42.5	none
aluminium, production mix, wr...	metals/extraction	Mass	g	42.5	none
injection moulding - RER	plastics/processing	Mass	g	66.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PC DVD-R		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
CD-ROM/DVD-ROM drive, des...	electronics/component	Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
DVD-R drive manufacture		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	0.157*1825	none
Packaged PC DVD-R		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC DVD-R to consumer		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
DVD-R drive manufacture		Number of items	Item(s)	1.0	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	1.6892*1825	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
DVD drive to consumer		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
DVD drive to consumer		Number of items	Item(s)	1.0	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	23.542	none
PC DVD-R to consumer		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC DVD gameplay		Duration	h	158.0	none

PC without DVD Drive

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none
polycarbonate, at plant - RER	plastics/polymers	Mass	g	42.5	none
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
injection moulding - RER	plastics/processing	Mass	g	42.5	none
aluminium, production mix, wr...	metals/extraction	Mass	g	42.5	none
injection moulding - RER	plastics/processing	Mass	g	66.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PC DVD-R SA 5		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	0.157*1825	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
Packaged PC DVD-R SA 5		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC DVD-R to consumer SA 5		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	23.542	none
PC DVD-R to consumer SA 5		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC DVD gameplay SA 5		Duration	h	158.0	none

Digital Base Cases

PS3

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	2.3706	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	7.9019	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.6322	none
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	0.0593	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.6322	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 download to consumer		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 download to consumer		Number of items	Item(s)	1.0	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	21.9462	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 download gameplay		Duration	h	158.0	none

PS4

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	1.1454	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	1.1454	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	4.2952	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	0.0945	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	14.3174	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 download to consumer		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 download to consumer		Number of items	Item(s)	1.0	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	20.0028	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 download gameplay		Duration	h	158.0	none

PC

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	1.5513	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	5.8172	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	0.0194	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	1.5513	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	19.3907	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC digital download		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	23.542	none
PC digital download		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC download gameplay		Duration	h	158.0	none

Sensitivity Analysis 1 – Higher Energy Efficiency in Internet Data Transfer

PS3

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	0.0593	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.9877	none
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	0.2963	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.079	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.079	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 download SA 1		Number of items	Item(s)	1.0	none

PS4

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	0.0945	none
electricity, high voltage, at grid...	electricity/supply mix	Energy	kWh	0.1432	none
electricity, high voltage, at grid...	electricity/supply mix	Energy	kWh	1.7897	none
electricity, high voltage, at grid...	electricity/supply mix	Energy	kWh	0.1432	none
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	0.5369	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 download SA 1		Number of items	Item(s)	1.0	none

PC

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	2.4238	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	0.1939	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	0.7272	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	0.0194	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	0.1939	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC download SA 1		Number of items	Item(s)	1.0	none

Sensitivity Analysis 2 – Average File Size Calculated with Non-Major Titles

PS3

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.0248	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	0.0248	none
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	1.1616	none
electricity, high voltage, at grid - US	electricity/supply mix	Energy	kWh	3.872	none
electricity, low voltage, at grid - US	electricity/supply mix	Energy	kWh	0.029	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 download SA 2		Number of items	Item(s)	1.0	none

PS4

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	7.0135	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	0.5612	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	0.5612	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	2.1041	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	0.0461	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 download SA 2		Number of items	Item(s)	1.0	none

PC

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	2.8503	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	9.501	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	0.7601	none
electricity, high voltage, at gri...	electricity/supply mix	Energy	kWh	0.7601	none
electricity, low voltage, at grid...	electricity/supply mix	Energy	kWh	0.0095	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC download SA 2		Number of items	Item(s)	1.0	none

Sensitivity Analysis 3 – Silver Alloy

PS3

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
polycarbonate, at plant - RER	plastics/polymers	Mass	g	15.47	none
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none
silver, at regional storage - RER	metals/extraction	Mass	g	1.53	none
injection moulding - RER	plastics/processing	Mass	g	15.47	none
injection moulding - RER	plastics/processing	Mass	g	66.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS3 blu ray SA 3		Number of items	Item(s)	1.0	none

PS4

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
injection moulding - RER	plastics/processing	Mass	g	15.47	none
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
silver, at regional storage - RER	metals/extraction	Mass	g	1.53	none
injection moulding - RER	plastics/processing	Mass	g	66.0	none
polycarbonate, at plant - RER	plastics/polymers	Mass	g	15.47	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS4 blu ray SA 3		Number of items	Item(s)	1.0	none

PC

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
injection moulding - RER	plastics/processing	Mass	g	42.5	none
injection moulding - RER	plastics/processing	Mass	g	42.5	none
silver, at regional storage - RER	metals/extraction	Mass	g	42.5	none
polycarbonate, at plant - RER	plastics/polymers	Mass	g	42.5	none
polypropylene, granulate, at pl...	plastics/polymers	Mass	g	66.0	none
paper, woodfree, coated, at re...	paper & cardboard/grap...	Mass	g	6.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PC DVD SA 3		Number of items	Item(s)	1.0	none

Sensitivity Analysis 4 – Higher and Lower Transportation Distances

PS3

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS3 blu ray SA 4 lo...		Number of items	Item(s)	1.0	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.089*980	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 blu ray to consumer SA 4...		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
Packaged PS3 blu ray SA 4 up...		Number of items	Item(s)	1.0	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.089*3400	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS3 blu ray to consumer SA 4...		Number of items	Item(s)	1.0	none

PS4

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
PS4 blu ray SA 4 lower bound		Number of items	Item(s)	1.0	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.089*980	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 blu ray to consumer SA 4...		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.089*3400	none
Packaged PS4 blu ray SA 4 up...		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PS4 blu ray to consumer SA 4...		Number of items	Item(s)	1.0	none

PC

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
DVD-R drive manufacture SA...		Number of items	Item(s)	1.0	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	1.6892*980	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
DVD drive to consumer SA 4 lo...		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	.157*980	none
Packaged PC DVD SA 4 lower...		Number of items	Item(s)	1.0	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC DVD to consumer SA 4 low...		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	1.6892*3400	none
DVD-R drive manufacture SA u...		Number of items	Item(s)	1.0	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
DVD drive to consumer SA 4 u...		Number of items	Item(s)	1.0	none

Inputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
transport, lorry >16t, fleet ave...	transport systems/road	Goods transpor...	kg*km	0.157*3400	none
Packaged PC DVD SA 4 upper...		Number of items	Item(s)	1.0	none
transport, passenger car - RER	transport systems/road	Person transport	p*km	1*20.6	none

Outputs

Flow	Category	Flow property	Unit	Amount	Uncertainty
PC DVD to consumer SA 4 upp...		Number of items	Item(s)	1.0	none