Life Cycle Assessment: Film vs Digital

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Abstract

Filmmakers have two options for shooting media − traditional analog film rolls and digital memory cards. While film industry experts may be well-versed in the stylistic implications of each method, there are few comprehensive resources comparing the different environmental implications. The following study helps to fill this gap through a comparative life-cycle assessment (LCA) of 35mm film versus digital semiconductor recording technologies to equip filmmakers with the environmental context necessary for making an informed choice. We compare the two alternatives on the basis of four different life cycle environmental burdens: energy use, water use, CO_2 equivalent (CO_2e) emissions, and hazardous waste. Data was collected through literature review and technical interviews with film and semiconductor chip experts. We used this data to create an interactive Excel tool that approximates the environmental impacts of choosing film versus digital for a user-specified duration of footage. For energy and water use, our findings indicate that film bares significantly greater environmental impacts than digital. The differences for CO_2e emissions and hazardous waste generation are less dramatic, but still greater for film. Our results indicate that an hour of unedited 35mm film footage requires 180 times more energy and 224 times more water, while generating 3.4 times more CO_2e emissions and 1.5 times more hazardous waste. Moving forward, this report and accompanying Excel tool seek to promote environmentally-conscious decision making in the film industry. Future research in this area could help to address identified gaps in existing LCAs for digital memory cards and film.

Introduction

Background

The television industry contributes to a range of environmental burdens, from climate change to air and water pollution. Seemingly innocuous choices made throughout the production process affect which of these impacts are manifested. This report focuses on the implications of the choice between two medium alternatives for capturing content – traditional 35mm film and digital memory cards. Filmmakers and audiences alike have long debated the aesthetic, economic, and technical merits of these media.

Many value 35mm film for its unique visual appeal. Unlike the fixed grid pixels of content shot digitally, the random distribution of film grains creates a quality many consider pleasing to the eye (Loertscher et al., 7). Arguments for the continued use of 35mm film in the motion picture industry largely stem from a preference for this aesthetic effect. However, with digital production, artistic freedom now includes the ability to enhance aesthetics in regards to color timing and various other image variables (Prince, 27).

In terms of practicality of use, a key benefit of the digital format for filmmakers is that it allows for immediate playback of recorded clips to determine when a scene needs to be reshot (Mann and Picard, 1). In contrast, film requires development and scanning to computers before it can be reviewed. The digital medium is also less expensive. Though both film and digital require upfront camera costs, film cameras require new film to be purchased continuously, whereas digital cameras store footage on memory cards that can be used beyond the scope of a single project. Furthermore, digital cameras tend to be cheaper because they are more widely available (Frazer et al., 249).

Another less emphasized benefit of traditional film is the fact that, in the future, 35mm films will be able to be rescanned to improve their current resolution levels. Due to the nature of digital and analog film technologies, digital footage is limited to the resolution in which it is shot, while film footage is limited by the resolution in which it is scanned. This is because there is no visual information between the pixels within the fixed grid of digital media, but there is visual information within grains of analog film that can be captured further at higher resolutions. At present, this does not impact filmmaking significantly, because screen technologies with resolutions greater than the standard 400 to 800 pixels are not yet widely available, so digital content is shot in the appropriate resolution. However, as high-resolution screen technologies are developed, the process of updating current analog films will be less intensive than digital, as it is a matter of being rescanned versus going through and generating new visual information (HBO Executives).

The environmental implications of film and digital production have begun to garner significant attention only in the last decade. The British Academy of Film and Television Arts developed a carbon calculator tool, "Albert," in 2011 to assist productions with tracking their carbon footprints ("An Introduction to Albert"). The tool has gained increasing popularity and is now used to generate annual reports of industry-wide progress ("All About Albert"). In March of 2021, the Sustainable Production Alliance – a consortium of Hollywood's biggest producers working to improve sustainability in the industry – published a review of carbon emissions from feature-length film and television productions between 2016 and 2019, accounting for contributions from housing, air travel, fuel and utilities ("Carbon Emissions" 2). While these works offer important insight into the carbon impacts of production and further the conversation around sustainability in the film industry, significant gaps in understanding how the environmental impacts differ between film and digital productions persist.

The following report hopes to contribute to this body of work through a comparative Life Cycle Assessment (LCA) of the impacts of capturing an hour of footage on 35mm cinematic film stocks as opposed to a digital memory card. Due to the reusability of digital memory cards and lack of development chemicals required, we expect capturing content digitally to be the more environmentally-friendly option.

Given that aesthetic and artistic value are subjective elements, and that issues of resolution are unlikely to arise in the near future, this project does not seek to dissuade filmmakers from one medium over the other, but rather to collect and organize data on the environmental impacts of each option to enable informed decision making.

While we have relied on reasonable methodologies with sound comparisons, an LCA without product level data (obtained either through laboratory analysis or through working closely with manufacturers) leaves significant levels of uncertainty. Thus, this study serves as a knowledge creation project, providing an elementary comparison between 35mm film and digital memory cards. This report dives deeper into the life cycle impacts of both technologies and identifies the data gaps preventing a more accurate comparison. This will be a foundation upon which future research with greater access to product level data can build.

Research Question

1. Based on existing data as well as data generated through the methods described in this proposal, what are the differences between the final footprints of shooting on film versus shooting digitally in terms of the following impact indicators?

Energy use, water use, CO_2e emissions, and hazardous waste

Literature Review

Our preliminary research involved reviewing existing literature on the Life Cycle Assessment (LCA) approach and on past applications of this approach to analog film and digital SD cards.

LCA Fundamentals

A Life Cycle Assessment (LCA) is an analytical tool used to determine potential social, environmental, and economic impacts of a product, process, or service throughout its life cycle, from raw material extraction to disposal (Finnveden, 1; SAIC and Curran, 1). LCAs rarely ascertain exact impacts, as this requires direct measurement and product-level primary data. Despite this, LCAs are becoming increasingly important for businesses seeking to improve environmental performance and for guiding environmental policy (Guinee et al., 90; Finnveden, 2).

LCA Framework

The LCA framework includes four stages: goal definition and scoping, inventory analysis, impact assessment, and interpretation (SAIC and Curran, 2).

The first stage, goal definition and scoping, involves constraining the study bounds to the specific processes, inputs, and outputs of interest. This stage establishes the intended application and audience of the LCA (Finnveden, 2). Stage one also includes defining the functional unit, which is a quantification of the product's purpose (SAIC and Curran, 11). Functional units are used to draw a direct comparison between products per unit of use, and are the measures by which impacts are quantified in an LCA (ECOIL, 3). A common challenge intertwined in selecting a functional unit is ensuring that it accurately encapsulates the purpose of the product or process, such that it can be used to compare with other products or processes offering the same purpose (ECOIL, 3). With this in mind, the functional unit for our LCA was defined as "*per hour of editable footage*."

The second stage, inventory analysis, consists of identifying and quantifying impact indicators (SAIC and Curran, 2). Impact indicators are the variables by which environmental performance can be measured quantitatively (Brown et al., 4). The impact indicators we analyzed to assess the environmental impact of film and digital in our LCAs are as follows: energy use, water use, CO_2e emissions, and hazardous waste.

Impact analysis occurs third, and involves assessing the items listed in the inventory analysis for their human and ecological impacts (SAIC and Curran, 2). Finally, the fourth stage of interpretation discusses product recommendations (SAIC and Curran, 2).

LCA Methodologies

LCAs can be conducted using one of three methodologies: process flow, input-output, and hybrid. Process flow approach involves constructing a branching tree diagram to model key processes associated with a given product, starting from the final point of analysis and working backwards up the supply chain. For each process, relevant inputs and outputs of material or energy are quantified. Input-Output approach breaks down the economy into individual economic sectors. By doing this we can represent multiple inputs required to produce a unit of output within a specific economic sector. This data is based on surveys of purchases and sales within various industries (Matthews, 222–23).

To complete our desired LCA for film versus digital, we will need to combine elements from both the process flow and the input-output approaches. This method is referred to as hybrid LCA. Hybrid LCA generally uses process flow as the core model and takes elements from input-output where needed to fill gaps in available data (Matthews, 316). Due to the fact that much of the data needed to conduct a full process flow analysis of film and digital memory cards is unavailable to us, we employed a hybrid approach and accounted for gaps with economic sector-scale input-output data.

Comparative LCA

A variation of the LCA approach can be used to compare different products that fulfill the same purpose and follow similar life cycles. The comparative LCA allows researchers to focus on the points in both product's life cycles where their impacts diverge most significantly to determine which is more sustainable, rather than building a full LCA for each product (Matthews 86). This method is well suited to our project given our limited resources and the similarities in the processes film and digital footage undergoes after it is processed and prepared for editing.

LCAs on Semiconductors

SD cards, also referred to as digital memory cards in this report, can be inserted into a digital camera to store footage. An SD card consists of a semiconductor memory chip cased in plastic packaging. The impacts associated with producing a memory chip are much greater than those of casing the chip in plastic ("Koho"). As such, we focused our literature review on the life cycle impacts of semiconductor chips.

Existing LCAs on semiconductor chips for SD cards summarize the manufacturing processes as: raw material extraction, purification, manufacturing, and transportation. While there is relatively extensive research for raw material extraction and manufacturing, data pertaining to purification and transportation is lacking (Williams et al., 5504). Past research largely focuses on the same impact indicators selected for this report: energy use, water use, CO_2e emissions, and hazardous waste generation.

Before chip fabrication can begin, the metals and other raw materials that semiconductor chips are composed of must first be mined. Silicon is the primary raw material used, alongside others like cerium and samarium (Villard et al., 103). Mining for raw materials results in negative effects on the natural environment due to practices such as open-pit mining that permanently change the physical landscape (Villard et al., 103).

Studies have found that about 48-58% of total energy consumption in the manufacturing of semiconductor chips occurs during the fabrication stage (Williams et al., 5506). At this stage, quartz is manipulated into silicon to create silicon wafers that are cut into square dies to be bonded and sealed with other metals and chemicals to create the internal memory. This area of research in current LCAs is expansive, with the most thorough findings and reported values related to our impact indicators.

The water, gas, chemicals, and raw materials used in the manufacturing stage must be ultra-purified to maintain the highest caliber of sanitation (Williams et al., 5507). Some studies predict that purification uses more energy than the actual fabrication of the chips, but these impacts are consistently underreported because existing LCAs only partially account for purification's impacts (Williams et al., 5507). This underestimation occurs because while information pertaining to bulk chemicals produced at "technical grades" is readily available, the impacts of ultra-pure grading are less widely understood (Plepys, 160). Further, individual companies typically report their values anonymously, preventing third-party verification (Betts, 8A). In addition to inaccurate energy values, some research suggests that Toxic Release Inventory (TRI) data is also under-reported (Williams et al., 5509). Future research should seek to improve estimates for purification-stage impacts — especially as chips become more complex and demand higher levels of purity.

While most current LCAs encompass most stages in semiconductor life cycles, some processes were not analyzed due to large variability in the data. The end-of-life disposal phase for semiconductor chips introduces unique challenges of e-waste and toxic leaching in landfills. However, because consumers are often responsible for semiconductor disposal, the semiconductor industry does not track disposal streams, leading to a gap in available information for LCAs (Villard et al., 103). Additionally, many LCAs do not focus on the impacts of transportation, arguing that the low mass of semiconductor chips renders this phase less impactful. Instead, researchers choose to focus on the more impactful stages as reviewed above (Villard et al., 105).

LCAs on Film Material

Basic film structure is made up of a cellulose acetate base with very thin emulsion layers laid on top, as shown by the cross-section of film displayed in figure 1. The alternating layers labeled "a" and "b" along the top indicate three overcoats (a); separating three emulsion layers (b) with black, white, or color "panchromatic sensitization" respectively; followed by a "subbing" layer (d); a cellulose acetate film base (i), and finally a supportive backing (h). It should be noted that figure 1 is not to scale. The cellulose acetate base is approximately 115-130 um thick, while the three emulsion layers combined are only 12-25 um thick (Keller et al. 139). Of particular note is the silver halide integral to the emulsion layers (Keller et al. 12-18). Silver halide microcrystals in the emulsion layers are what make the film capable of sensing incoming light and storing visual information. When introduced to reducing agents during the development of the film, these silver halide microcrystals reduce to metallic silver (Keller et al. 6). Silver halide microcrystals and silver atoms have particularly dangerous environmental implications because free silver ions are highly toxic, particularly for aquatic environments (Keller et al. 157). Given that the cellulose acetate base makes up the vast majority of the film's volume and that the silver in the emulsion layers poses significant environmental impacts, focusing specifically on the base and the emulsion layers in LCAs of film is critical.

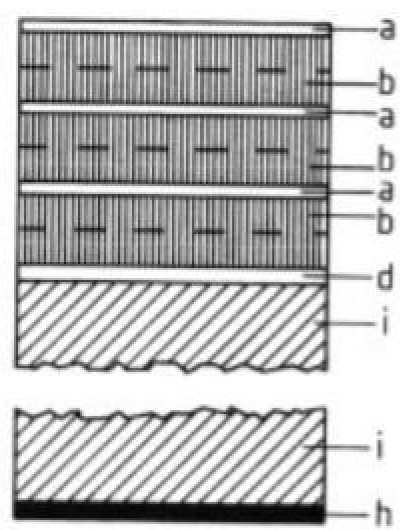

Figure 1: Diagram showing cross section of 35mm cinematic film - not to scale (Keller et al. 139).

Existing LCA research on film material for motion picture production is limited. Despite extensive searches of scholarly databases (Google Scholar, Springer Link, JSTOR, and Web of Science), little publicly-available research could be located detailing the full life cycle impacts of cinematic film. The absence of this data presented immense challenges for this project and highlighted the salience of further research in this field. LCA literature on 35mm photographic film serves as a useful substitute for research on 35mm cinematic film because still and cinematic film require comparable material and energy inputs during manufacturing and development. Previous photographic film LCAs have relied on functional units of one 4" by 6" color image or approximately 1 roll of processed film (25 pieces of 4" by 6" images), while others have measured impacts per camera unit (Bras et al. 551; Delaveau 32; B. Yang et al. 309). In terms of scope, one study of photographic film, for which the Eastman Kodak Company was a collaborator, confined their work to four phases. The first "upstream" phase encompassed three sub-categories—material gathering, refining, and manufacturing. The following three phases were defined as distribution, use, and end-of-life disposal (Bras et al. 550). Alternatively, a different study considered design, material procurement, and manufacturing to all be distinct independent steps (B. Yang et al., 304). One study comparing film and digital still photography found that film's environmental burden predominantly stemmed from its use phase, while upstream impacts comprised the brunt of digital's burden. However, the article noted that different use behaviors — such as varied times spent on digital photo editing — could substantially affect results and should be accounted for in future research (Bras et al. 554).

Impact indicators were mostly uniform across the still photography LCA literature reviewed. Energy use, emissions, water use, and solid waste were consistently included, though some papers also accounted for environmental releases, chemical waste, photoprocessing solution use, and silver emissions (Bras et al. 551; Delaveau 36; B. Yang et al. 304). Multiple studies highlighted chemical waste as film's most pressing environmental burden (Bras et al. 553; B. Yang et al. 307).

Methodology

Scope Definition

The scope for this Comparative LCA of analog film and digital SD cards was defined in consultation with our clients to address their expectations while adhering to resource and time constraints. We confined our scope to the environmental impacts associated with one hour of analog versus digital unedited footage for a television series filmed within a major shooting market. We specified a functional unit of "*per hour of editable footage"* and impact indicators of energy use, water use, CO_2e emissions, and hazardous waste generation.

Based on the specifications outlined in table 1, capturing an hour of footage on analog film requires 5,400 ft of film. This is the value we use for our analysis. For digital, we are honing our analysis to the storage of 1 hour of footage on a 1 TB SD card. While filmmakers shoot for 1.5 to 4 hours per day on average, storage of footage on the higher end of that range is divided into multiple cards so that download speed is more efficient and economical (HBO Executives, et al.). It is estimated that an hour of content shot digitally, at 4K resolution, requires approximately 1 TB of storage (HBO Executives, et al.). Therefore, it is reasonable to assume that an HBO production would store a single hour of footage on a single 1TB SD card.

Though neither analog film nor digital footage may be captured without a camera body, our scope excludes the impacts associated with camera bodies since their lifespans render their impacts per hour of footage insignificant. Further, we omitted use-phase impacts in our analysis because individual decisions of filmmakers on set vary too greatly to be approximated. Lighting equipment choices in particular may differ between television series shot on 35mm film versus digital SD cards, but we came to the conclusion that this area of study was better suited to a project with greater resources. Defining our scope with these specifications provides the framework for a standardized comparison between capturing footage on 35mm film and on digital SD cards, while limiting our inclusion of impacts to processes that may be highly variable between Hollywood productions.

Our scope is specified for television series footage so that we can reasonably omit the impacts of cutting analog film at dailies facilities. "Dailies" refers to the footage that is sent to a processing—dailies—facility to be prepped for review and editing. Processing procedures at dailies facilities include development and scanning for analog film as well as color correction and audio-visual matching for both film and digital footage. While all footage captured on 35mm film is digitized at a dailies facility, physically cutting film is a process that almost exclusively applies to feature-length films.

Our scope is specified for footage shot within a major shooting market, ie. Los Angeles or New York City, so we can assume that ground transport is used for dailies and no footage is shipped by air from sets to their respective dailies facilities. It is also specified for one hour of unedited footage because the amount of footage needed to finalize a film varies between productions based on number of takes (HBO Executives, et al.). The scope of our study omits shooting phases and ends after analog film is scanned at a dailies facility because there is too much variation in use-phases between productions, and the impacts of analog film are indistinguishable from digital once they are digitized and transferred onto digital hard drives.

This study does not address end-of-life waste streams because productions typically store their developed film indefinitely in underground archival facilities. Meanwhile, the semiconductor chip industry does not track end-of-life disposal due to a disconnect between manufacturers, third-party distributors of digital SD cards, and consumers. However, we assume SD cards are reused enough times to make their end-of-life waste stream impacts negligible per hour of unedited footage.

Film Type	Speed (fps)	Time	Total Frames	Length (ft)	1000 ft rolls
35-mm	24	1 hour	86400	5400	5.4

Table 1: Table illustrating the specifications of 35mm cinematic film, particularly the conversions between frames per second and length of film used.

Process Flow Diagrams

Following scope definition, our first step in carrying out the hybrid approach to Comparative LCA was to construct our process flow diagrams. Process flow diagrams are the branching tree figures of connected unit processes that make up a product's supply chain. Stage 0 refers to the set of unit processes that occur directly before the point of analysis for the final product. Stage 1 unit processes involve the manufacturing or procurement of inputs to the stage 0 processes. Each subsequent stage moves backwards through the supply chain and is numbered as stage 2, 3, etc. We follow supply chains backwards until credible lifecycle values are found, at which point we end the corresponding branches of the tree diagram and assign the appropriate values.

For film manufacturing, we elected to constrain our unit process flow diagrams and analysis to stage 0 and stage 1 impacts. Stage 0 refers to the final manufacturing of 35mm film at a Kodak factory. The stage 0 inputs that we traced back to stage 1 were the silver, obtained through silver mining, and the emulsion layers, obtained through emulsion chemicals manufacturing. Due to limited research on film-development impacts, our development unit process focused on stage 0 impacts and only considered additional stage 1 impacts associated with transportation to the development facility.

As for SD card manufacturing, stage 0 includes SD card packaging while stage 1 refers to semiconductor/memory chip manufacturing. While stage 2 unit processes for raw material extraction and purification were initially included in our diagram, our research led us to LCAs that include the impacts from those processes within the impacts of stage 1 semiconductor manufacturing. As such, we were able to terminate our process flow diagrams at stage 1. However, due to the limited literature available for purification, it should be noted that energy and water use values in this report represent lower bounds.

Across figures 2-4 below, the general sources used to derive various values are indicated in red boxes, and each individual process is contained in a blue box with the inputs and outputs signified with arrows.

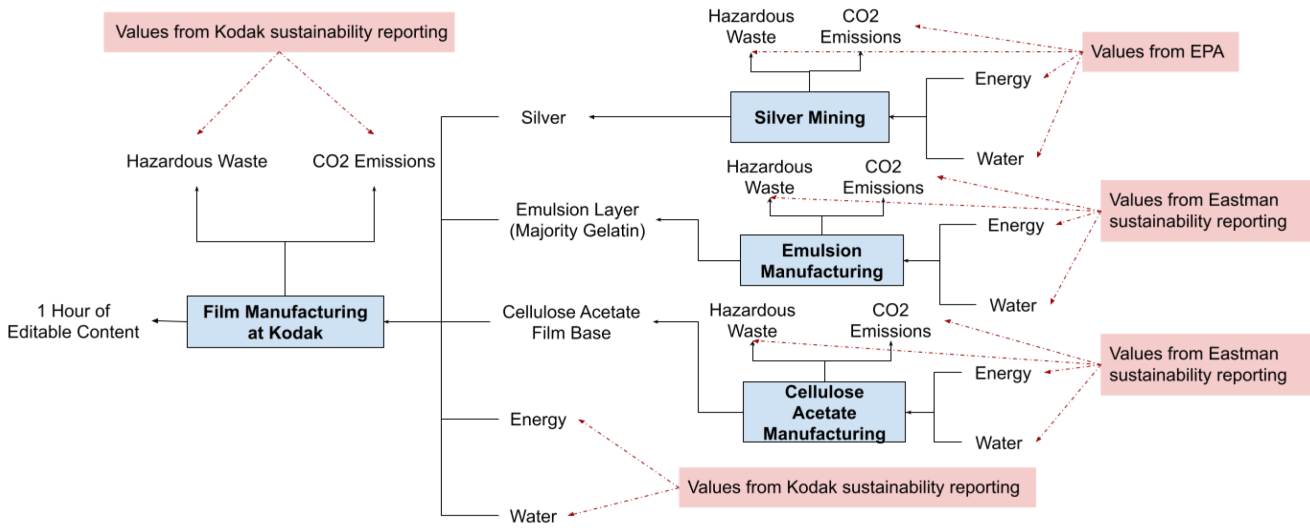

Figure 2: A breakdown of the unit processes going into film manufacturing. Blue boxes indicate the processes, red boxes indicate the source from which the metric values were derived.

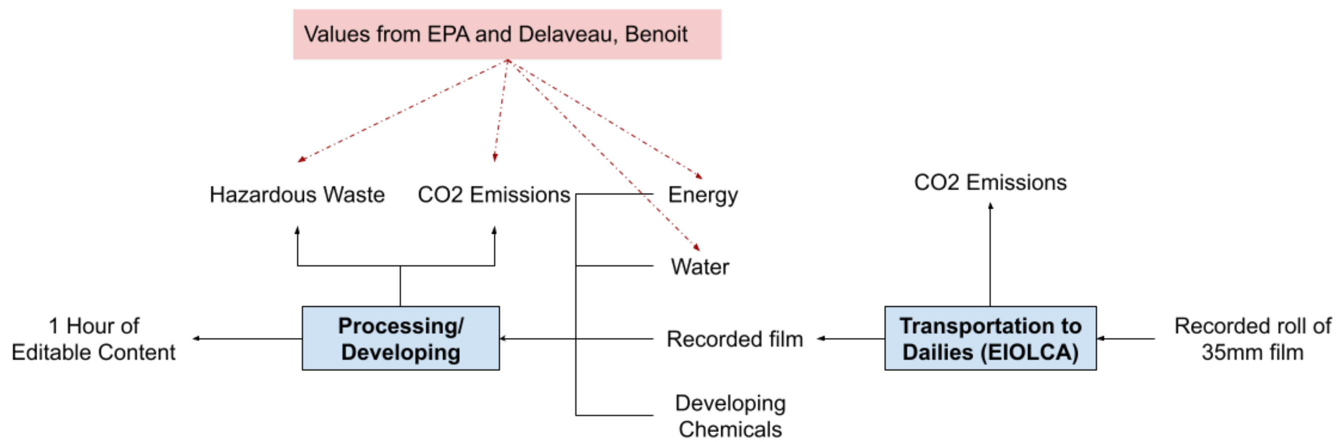

Figure 3: A breakdown of the unit processes for film development.

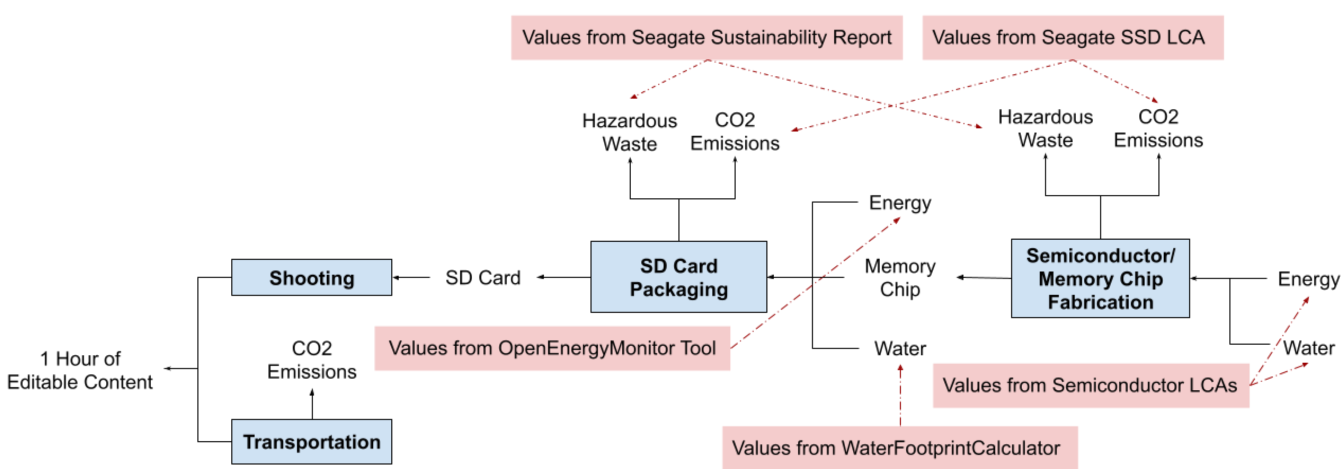

Figure 4: A breakdown of the unit processes going into SD card manufacturing.

Data Collection

Our research primarily depended on scientific literature, expert interviews, and government and industry reporting. Because we were not able to collaborate with film or digital semiconductor chip manufacturers directly, we were not privy to proprietary technical information and had to rely almost exclusively on publicly available data.

Film

For film-related values, other than the literature and HBO executive interviews cited below, we also relied on an interview with a former long-term Kodak employee who worked at the managerial level in the film manufacturing division and who wishes to remain unidentified. That interview offered the basis for the following assumptions:

1. Weight breakdown for film (including the amount of silver in film),
2. Approximate costs of chemicals in the emulsion layers, and
3. Kodak annual film production.

Raw Materials

The major components required for manufacturing film are as follows:

1. Cellulose acetate for the film base,
2. Gelatin and a mix of other chemicals for the emulsion layers, and
3. Silver for the emulsion layers.

The raw materials section of our excel sheet estimates the impacts associated with each of these components using Environmental Social Governance (ESG) data reported by Eastman Chemical Company, an EPA Environmentally Extended Input-Output (EEIO) Model, EPA RCRA Hazardous Waste reporting, expert interviews, and silver market records from the US Geological Services.

When considering the intermediate chemicals required for emulsion layer manufacturing, we focused on the impacts of gelatin, as gelatin makes up the bulk of the mass while other compounds are added only in smaller amounts. We assume that Kodak is sourcing cellulose acetate, gelatin, and all other intermediate chemicals needed for film manufacturing from Eastman Chemical. While Kodak's supply chain is held as a trade secret, it is fair to assume that Kodak sources from Eastman Chemical because both are part of the larger Eastman company and both have facilities housed within the Rochester Eastman Business Park ("About"; "Industries"; "Chemical Manufacturing"). Even if this assumption is misguided and Kodak sources from other chemical manufacturers, the impacts of those manufacturers are likely comparable to those of Eastman Chemical. Based on these assumptions on cellulose acetate and gelatin manufacturing, we relied on Eastman Chemicals's ESG data for all four impact indicators for both chemicals (Crawford; "Environmental Social Governance"). Their reporting documents include annual sales, annual impacts for a variety of metrics, as well as approximated impacts per kg production for certain metrics. From these values, we approximated impacts per USD ($) of production and the price per unit of cellulose acetate and gelatin.

To determine the impacts of silver mining, we utilized the EPA's Environmental Economic Input-Output (EEIO) Excel model to determine our values for energy use, CO_2e emissions, and water use (Y. Yang et al.). The excel table offers values for the environmental impacts associated with producing one 2013 USD ($) of output for nearly 400 industries (Y. Yang et al.). We utilized the "iron, gold, silver, and other metal ores/ US" industry, and looked at values for the "kg CO_2e equivalent," "energy (MJ)," and "water (m^3)" indicators. Unfortunately, EPA EEIO did not include a hazardous waste indicator. As such, we turned to the EPA's RCRA hazardous waste biennial records and found data for Hecla Mining Company's Lucky Friday Silver Mine in

Idaho in 2017 ("2017 Site Details"). We then found reporting on Hecla's website for silver production in 2017 and used these values to approximate hazardous waste production per kg of silver production ("Lucky Friday"). Using values for primary silver mining and secondary silver recycling from the US Geological Services, we were able to calculate the percent of silver newly mined in the US in 2013 (Katrivanos 1).

Our next step was to convert the values from "impact per mass of raw material" to reference flow values, meaning "impact per functional unit." In order to determine impact per hour of footage, we first needed to determine the breakdown of a film roll by mass. From there, we could make the impacts per mass of each raw material input proportional to the mass of that raw material input per foot of film, then multiply by the 5400 ft of film needed per hour of footage. We performed these calculations using values reported in the Photography entry in Ullmann's Encyclopedia of Industrial Chemistry (Keller et al.). We were able to verify and refine these numbers through our interviews and correspondence with our Kodak contact to arrive at an appropriate weight breakdown for the basis of our raw materials impacts.

Manufacturing

The film manufacturing section of our Excel sheet aims to account for the environmental impacts of Kodak's Consumer and Film sector, whose operations are responsible for cinematic film production. While our background research offered a general understanding of the steps that go into manufacturing film, the specifics needed to gauge the impacts attributable to each individual step throughout the umbrella of manufacturing were unavailable at the public level. However, the Eastman Kodak Company has a monopoly in Hollywood's cinematic film market. We were able to assess the aggregate impacts of manufacturing as a broad category using Kodak's 2017 Corporate Responsibility Report and Eastman Kodak Company's 2017 Annual Report to estimate the annual emissions of cinematic film production within their operations (SITE). We also used the chemical industry averages to calculate emission expectations for Kodak's production of 35mm cinematic film based on industry standards to build confidence in our values.

Kodak's 2017 Corporate Responsibility Report reports values for each of the four environmental impact categories addressed in our analysis: energy and water usage as well as CO_2e and hazardous waste emissions for total worldwide operations. With those values, we used Kodak's 2017 Annual Report to devise assumptions for the percentage of worldwide impacts attributable to Kodak's Consumer and Film sector operations. From the annual report we found that Consumer and Film was one of seven sectors operated by Kodak in 2017 and that Kodak's Consumer and Film sector has operations in 2 out of 10 global manufacturing locations. Using Consumer and Film's Net Sales for the year, minus the total earnings from its operation, we loosely gauged the operating costs of Consumer and Film shared between those two facilities. We then divided those against global operating costs found in Kodak's Global Net Sales for the year, minus their total earnings from operations between their 10 facilities. Considering the fact that Consumer and Film is one of seven sectors pulling in revenue for Kodak, we divided the ratio of Consumer and Film operating costs per facility and Global operating costs per facility by 7. While we recognize that financial reporting does not directly correspond to impact assessment, we used those ratios to approximate impact attribution for Consumer and Film operations in the absence of more accurate data. We assume our manipulated percent of impacts attributable to Consumer and Film at Eastman Business Park is either on par or an overestimate of the sector's true demand, especially because the worldwide emissions include overhead impacts as well. With this in mind, we used the feet of film produced per year and the feet of film per hour of editable footage to find the impacts of cinematic film manufacturing per hour of editable footage.

Based on Kodak's 2017 Annual Report, we found that Kodak's Consumer and Film sector operates almost exclusively from Eastman Business Park in Rochester, New York. Using a map of the park from RED Rochester—an energy company operating within the park, we approximated the total square footage of buildings owned *and* operated by Kodak within the park (Park Maps Eastman Business Park). Then, using the average energy usage of a manufacturing plant per square foot per year found from Business Energy Advisor, we calculated the amount of energy used by Kodak at Eastman Business Park per year (E Source Companies LLC.). With that energy usage value, we applied the chemical manufacturing energy to water ratio from Rao, et al., 2017 and the CO_2e emission factor per unit of energy from the EPA to calculate yearly water usage and CO_2e emission expectations (Greenhouse Gas Equivalencies Calculator, 2020). Based on the Annual Report, we found that five sectors under Kodak operations perform functions at Eastman Business Park, so we applied the assumption that approximately 20% of impacts born at the Park are attributable to Consumer and Film. Though this assumption is somewhat arbitrary, updating the input percent value would be a straightforward process for a future project with access to more refined data. After calculating energy and water usage and CO_2e emissions per year, we again used the feet of film produced per year and the feet of film per hour of editable footage to solve for the energy, water, and greenhouse gas emission impacts per hour of editable film. Calculating the impacts associated with manufacturing per hour of editable content using both Kodak's Corporate Responsibility Report from 2017 and industry averages resulted in values of similar magnitudes, lending to our confidence in reasonability.

<u>Development</u>

Despite extensive research into the film development process, we found few values that would be useful for determining its environmental impacts. Initially, we researched the chemical combinations and replenishment rates used for developing solutions. However, we were unable to find critical values needed to convert these into reference flow values.

We turned to a previous LCA of the photoprocessing industry that focused on film paper development (Covington 1). The *Preliminary Data Summary for Photoprocessing Industry* report provided specific values for wastewater and hazardous chemicals present in effluent from developing film paper. Operating under the assumption that equal areas of 35mm film and 35mm film paper use water at a 4:1 ratio, we approximated the water use and hazardous waste impacts of developing cinematic film from these values (Delaveau 71).

The remaining two impact categories, energy and CO_2e, had the least publicly available data. We ultimately relied on values from a San Jose State University masters thesis titled, *The Environmental Impact of the Retail Photoprocessing Industry in Santa Clara* (Delaveau 40-74). Their research analyzed the energy demand, greenhouse gas emissions, silver discharge, and water consumption of the retail still photoprocessing industry in Santa Clara, reporting on two photoprocessing facilities in the area, one of which is the largest photoprocessing facility in the San Francisco Bay Area. Using this data, we calculated both the energy demand and the greenhouse gas emissions associated with developing 5,4000 ft of film, amounting to one hour of editable content. We cannot confirm whether there is a linear correlation between the energy used and CO_2e emitted per still photography exposure, when extended to the exposures needed for an hour of motion picture film; therefore, our reported values may overestimate the impact values of these two categories. However, we were unable to find more accurate data, so these calculations serve as the most accurate estimation of the energy and CO_2e impacts for developing an hour of content given this project's time and resource limitations.

Digital

<u>Raw Materials</u>

In researching the raw materials used to produce SD cards, we focused on the three major materials influencing our impact indicators the most: copper, resin epoxy, and quartz. Quartz is the main component in dies, copper is used for a chip's copper lead frame, and resin epoxy is used to make a chip's packaging (Williams et al., 5508). We used data from the EPA's EEIO Excel model to identify values for all of the impact indicators except hazardous waste (Y. Yang et al.). We utilized the industry classifications "copper, nickel, lead, and zinc/US", "plastics/US", and "other nonmetallic mineral products/US", and the "kg CO_2 equivalent," "energy (MJ)," and "water (m^3)" indicators. Although these were initially included in our results, the impacts associated with raw material extraction have since been omitted from our final values as we found more relevant LCAs that encompassed raw material extraction in their values for manufacturing.

<u>Manufacturing</u>

We initially researched three key stages of SD card manufacturing: on-site material purification, front-end chip fabrication, and back-end chip assembly. The early stages of our research consisted of finding past LCAs and other literature on semiconductor chips. As an integral feature of electronic devices, semiconductor chips have been the focus of extensive research. We were able to find a number of robust sources with data pertaining to our impact indicators. We categorized data from these credible sources into the three key stages as listed above and added them to our Excel tool.

Within this first step, we identified the gaps in current publicly available LCAs. Of the sources we used, we discerned several themes across the board in semiconductor chip LCAs:

- Transportation is often unaccounted for.
- Purification research is scarce and often resides solely with companies, thus impacts have not been fully encompassed in current LCAs.
- Front-end chip fabrication and back-end chip assembly are considered to require the most inputs.
- Consumer usage is the most energy-intensive phase.

At this stage, we had exhausted the sources we were able to find online and turned to expert interviews to gather additional information.

In total, we contacted four experts in the semiconductor industry but were only successful in receiving responses from UCLA Professor Puneet Gupta. In our initial interview with Professor Gupta, we asked him questions related to SD storage and memory, raw material extraction, and processing (Gupta). We were able to gather information regarding the storage capacity per die and the shift in standard wafer size from 150mm to 3000mm (Gupta). Through correspondence with Professor Gupta, we were able to conclude that existing LCAs do not cover the specific breakdown of raw material extraction and purification impacts and that relying on manufacturing data that encompassed these stages provided sufficiently accurate values.

After attempting to find impact values for each individual process, we shifted our approach for data collection to existing LCA values that reflect the combined impacts of all production stages—raw material extraction to chip manufacturing—for each impact indicator. For our final values for energy and water usage indicator, we relied on *The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices* (Williams et al.), which is also cited as a reliable source in several other LCA reports. The values for these two indicators did not completely encompass SD card manufacturing, as they did not include values for SD card casing. Instead, the values used to identify energy and water usage for the plastic casing process were found from the *OpenEnergyMonitor* and *WaterFootprintCalculator,* respectively ("The Hidden", "Plastics"). These two sources gave us the energy and water use it takes to produce one pound of plastic which we then converted to grams (g) to account for the actual weight of the SD card packaging. The standard weight of an SD card is 3 g, with its semiconductor chip weighing 2 g. Therefore, the weight of the plastic SD card packaging is approximately 1 g ("SDHC", Williams et al. 5508).

As for hazardous waste and CO_2e emissions, we relied on values for solid state drives (SSDs) because Professor Gupta informed us that SD cards and SSDs are extremely similar in composition. These indicator values were estimated using data from the *Seagate Koho Enterprise Solid-State Drive Product Life Cycle Assessment Summary* and the *Nytro 1551 Sustainability Report* ("Koho", "Nytro"). The values for CO_2e emissions, which fully encompassed raw material extraction to SSD assembly, were taken directly from the Seagate LCA. Since very few semiconductor or SSD LCAs mention hazardous waste as an output, we decided to use "ecotoxicity" and "human toxicity" as a way to represent hazardous waste values. It is known in the semiconductor industry that 99% of all ecotoxicity outputs are released as a direct result of electricity generation (Boyd, 90). We used the Nytro sustainability report to determine the amount of hazardous waste released as a direct result of electricity generation, from raw material extraction to final product assembly ("Nytro").

While various types of SD cards with varying storage capacities are used on sets, 1 TB SD cards are used as well (HBO Executives, et al.). For the purpose of finding reference flow values as "impact per hour of digital content," we used the rates of "1 TB per SD card" and "1 SD card per hour of digital content."

Transportation

Footage captured on both film and SD cards requires transportation to a dailies facility after shooting. Two round trips are typically made to the dailies facility per day — one at lunchtime and one at the end of the day (Gonzalez). For a production in a major shooting market, the maximum distance from set to a dailies facility would be approximately 30 miles (Gonzalez). Under this assumption, two round trips amounts to 120 miles total per day (30 miles/trip * 2 trips/round trip * 2 round trips/day). However, even in major shooting markets, there are fewer facilities with the amenities needed to process film than to process SD cards (Gonzalez). As a result, film typically has to travel farther than SD cards do to reach an appropriate dailies facility. This difference amounts to an extra 10 miles of travel per day on average for a film production than a digital production, resulting in 120 miles of travel for digital compared to 130 miles for 35mm film (Gonzalez).

Depending on the production and the day, the hours of footage transported per round trip varies greatly. In order to avoid under-estimating impacts and remain within our scope, we assume that only a single hour of footage is transported per round trip. Based on this, an hour of digital footage is assigned the impacts of 60 miles of travel (120 miles/2 round trips = 60 miles per round trip), while an hour of film footage is assigned the impacts of 65 miles of travel (130 miles/2 round trips = 65 miles per round trip).

In order to calculate the CO_2e emissions associated with this transportation, we used the Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool. The AFLEET tool was created by the Argonne National Laboratory for the Department of Energy to compare new alternative fuel vehicles against diesel and gasoline vehicles according to petroleum use, greenhouse gas emissions, air pollutant emissions, and simple payback. Users begin by selecting their vehicle type. Due to uncertainty in the types of vehicles used to transport 35mm film and SD cards, we opted to run the model using a heavier duty vehicle − the single unit short-haul truck. The user then inputs the price of gas per gallon, the vehicle's fuel economy, and the vehicle's annual mileage. We set the gas price to $4 per gallon and the truck fuel economy to 10 miles per gallon ("State Gas Price Averages"; "15ft Moving Truck"). To get the annual mileage given the scope of our project, we multiplied both 60 miles and 65 miles by 365. The model output gave us the annual greenhouse gas emissions in short tons associated with our inputs. We then divided the two annual CO_2e emissions by 365 to find the amount of CO_2e emitted per 60 and 65 mile trip for digital and traditional 35mm film respectively.

Only CO_2e emissions were considered for transportation because this impact is the most significant at the scale of 60-65 miles of travel. Further, AFLEET does not provide information for energy use, water use, or hazardous waste. It should be noted that due to the compounding assumptions made in this section, the CO_2e emissions values for transportation are likely over-estimates.

Excel Design

Using the data we collected, we developed an interactive Excel tool that will enable filmmakers to see how the environmental impacts of their productions change when shot on film versus digital. The first sheet of the tool displays the total environmental impacts for film and digital in terms of energy (kWh/hr footage), hazardous waste (kg/hr footage), CO_2e emissions (kg/hr footage), and water (gal/hr footage) highlighted in green. On this sheet we have included a feature, indicated by the blue arrow, that allows users to input the number of hours of footage for which they would like to compare film versus digital impacts. While film features individual values for raw material extraction and manufacturing, digital's values for these processes are bundled together under one value since individual values for these processes are unavailable. On the "Film" and "SD Card" sheets of the excel, users will be able to see the data inputs and equations for calculating the environmental impacts of individual processes that culminate in the final values reported on the general sheet. Other sheets include reference to our sources and basic unit conversions. The Excel framework and our source transparency will allow future researchers to build upon our work and continue to fill knowledge gaps within this field of study.

Results

	Energy (kWh/hr footage)		Water (gal/hr footage)		CO_2e Emissions (kg/hr footage)		Hazardous Waste (kg/hr footage)	
Processes	**Film**	**Digital**	**Film**	**Digital**	**Film**	**Digital**	**Film**	**Digital**
Raw Materials	892.80	22.15	1376.06	12.34	183.20	90.76	0.05	1.62
Manufacturing	333.63		442.35		191.80		1.80	
Transportation					80.03	73.94		
Development	2763.28		942.68		106.23		0.56	
Total Impacts	**3989.71**	**22.15**	**2761.10**	**12.34**	**561.26**	**164.70**	**2.41**	**1.62**
Scale Factor	**180.12 : 1**		**223.75 : 1**		**3.36 : 1**		**1.49 : 1**	

Table 2: Table summarizing the results for total energy usage, water usage, CO2e emissions, and hazardous waste emissions in each of the four processes studied (ie. raw materials, manufacturing, transportation, and development) for film and digital.

Energy Use

Based on our results, we found that capturing an hour of footage on 5,400ft of 35mm film requires roughly 180 times more energy than capturing an hour of footage on a 1 TB SD card. Note the transport of both film and digital was deemed negligible in terms of energy use and is not included in this impact category.

An hour of footage on 35mm film requires 3989.71 kWh of energy in total from three processes.

1. Raw material mining and processing: 892.80 kWh per hour of footage
2. Film roll manufacturing and assembly: 333.63 kWh per hour of footage
3. Development: 2763.28 kWh per hour of footage

In contrast, the total lifecycle energy demand for an hour of footage on SD cards is only 22.15 kWh per hour of footage, which accounts for all four processes of raw material extraction, purification, chip manufacturing, and SD card packaging.

On-site purification is partially included in our analysis because data is not widely available. Values extracted from Williams include estimated energy used in purification; however, these values have a high degree of uncertainty due to variation in data likely caused by "technological improvements between data sampling times" (Williams, 5507). This is crucial to note as more current values of energy required for purification would increase our current findings.

Water Use

Our results indicate that film uses significantly more water than digital. The processes that contribute to water usage include raw materials and manufacturing for both film and digital, and development for 35mm film exclusively. Transportation contributions to water usage are negligible, so we did not consider them for either film or digital. The process of developing analog film uses roughly 942.69 gallons of water per hour, while manufacturing film uses approximately 442.35 gallons of water per hour. While these are both significant volumes, it is the raw material extraction and processing stage that accounts for the most water usage attributable to an hour of analog film footage with 1376.06 gallons of water per hour. Together, the total amount of water used for every hour of unedited film media equates to 2761.10 gallons.

In contrast, an hour of footage shot on digital SD cards uses a total of 12.34 gallons of water per hour between raw materials processing and manufacturing. This means that film uses nearly 224 times more gallons of water per hour of footage than digital does, making digital the much more sustainable option in terms of water use.

CO_2 Equivalent Emissions

Digital SD cards outperform film in terms of CO_2e emissions by a factor of 3. Capturing an hour of unedited footage on film generates 561.26 kg CO_2e, whereas capturing an hour of unedited footage on a digital SD card produces only 164.70 kg CO_2e, a difference of nearly 400 kg CO_2e.

For 35mm film, we reported the raw material and manufacturing impacts of an hour's worth of unedited media as individual processes; however, for digital SD cards we reported them as an aggregate process. If we compare the aggregate impacts of the raw material and manufacturing for 35mm film and digital SD cards, we find that producing 5400 feet of analog film has 4 times more CO_2e emissions than producing 1 SD card, with approximately 375.00 kg CO_2e and 90.76 kg CO_2e, respectively.

In terms of transportation, analog film emits more CO_2e than digital due to our assumption that analog film footage must be transported an average of 10 miles further per day, or 5 miles further per round trip, than digital footage to reach a dailies facility with development amenities. For total distance traveled, film contributes 80.03 kg of CO_2e per hour of unedited footage while digital contributes 73.94 kg of CO_2e per hour of unedited footage. This means that, on average, transporting film within a major shooting market emits 6.09 kg more CO_2e than digital per dailies trip. Additionally, the development phase contributes an additional 106.23 kg CO_2e to the final value for film.

Hazardous Waste

The hazardous waste impact for 35mm film is 2.41 kg per hour of footage, while the impact for digital SD cards is 1.62 kg per hour of footage, a difference of 0.79 kg per hour of footage or 49%. The processes that contribute to hazardous waste for film are as follows: raw materials, manufacturing, and development. Film manufacturing accounted for roughly 75% of the total hazardous waste, with a value of 1.80 kg of waste per hour of footage. For film's raw material extraction and development, these processes contributed 0.05 kg of hazardous waste per hour of footage and 0.56 kg of hazardous waste per hour footage, respectively. As for digital, since the footage does not need to be developed, only raw material extraction and manufacturing processes contribute to our reported hazardous waste values. However, we cannot state which process produces more hazardous waste for digital since raw material impacts are bundled together with manufacturing in our source data that was taken from previous LCAs and cannot be differentiated. Our overall findings indicate that digital is more sustainable than film in terms of hazardous waste impacts.

Sensitivity Analysis

Though we sought accurate data throughout our research process, certain limitations introduced inevitable uncertainty to our values. While these limitations will be discussed later in this report, the following sensitivity analysis considers how this uncertainty might affect our final values and overall finding that an hour of footage on digital memory cards has a better environmental performance across all impact categories considered in this report than an hour of footage on traditional film.

We first conducted an up-down sensitivity analysis to account for any over or underestimations made in the final values for film and digital. An up-down sensitivity analysis allows us to study the change in our results when we adjust the values for raw materials, manufacturing, transportation, and development up and down by 10%, 20%, 50%, 75%, and 80%. In terms of CO_2e emissions, film would remain more impactful than digital unless digital's impacts did not change or increased while film's impacts decreased by at least 75%. For energy and water use, film's impact values would remain greater than digital across every up-down trial, even if film's impacts were reduced and digital's impacts increased by 80% each. These results exhibit high confidence in digital outperforming film across these three impact indicators.

However, for hazardous waste, a reduction of film's impacts by as little as 20% would render it less impactful than digital's current hazardous waste impacts. This suggests that we cannot be as confident that an hour of footage on film produces greater amounts of hazardous waste than an hour of digital footage.

In addition to this general up-down analysis, we conducted sensitivity analyses on specific values of greater uncertainty from our calculations for both film and digital media.

Film

One value that we were particularly uncertain about for film was the percentage of silver in the emulsion layer that was mined as opposed to recycled. Documentation on the silver industry from the USGS indicated that nationally, 32% of silver refined in the US in 2013 was "primary" or newly mined, while the remainder was recycled. However, during our interview with the ex-Kodak employee, he estimated that as much as 90% of the silver used by Kodak is recycled. Our initial analysis relied on the USGS value, but later for sensitivity, we ran the numbers again assuming that only 10% was newly mined. The 32% and 10% scenarios are displayed in table 3 below. The largest change occurs for water, which drops 32.5% when we change the percent of newly mined silver from 32% to 10%. This amounts to 899 fewer gallons of water used for the silver demand of 5400 ft of film. CO2e emissions and energy decrease by 11.3% and 8.4%, respectively, translating to changes of 336 kWh and 64 kg CO2e. Only hazardous waste has virtually no change. This indicates that silver mining contributes less significantly to the hazardous waste impact of film, so our uncertainty in the percent of silver that is recycled has a lesser impact on this indicator.

Impact of Newly Mined Silver % on Total Impacts per 1 Hour Footage				
Indicator	**Units**	**Current Value (32%)**	**10% Scenario**	**% Change**
Energy	**kWh/1 hr footage**	3989.71	3653.84	-8.42
Water	**gal/1 hr footage**	2761.10	1862.64	-32.54
CO_2e Emissions	**kg CO_2e/1 hr footage**	561.26	497.64	-11.34
Hazardous Waste	**kg waste/1 hr footage**	2.41	2.41	-0.00091

Table 3: Table summarizing the results of 10% impact increase and reduction scenarios for newly mined silver.

Looking at figure 5a-d puts the variation in the energy and water values into context and reveals that our uncertainty with regards to the percent of newly mined silver used in film manufacturing is not significant enough to affect our overarching finding that film has substantially more environmental impacts than digital. Should the 10% scenario be correct, the scale of water and energy used for film versus digital diverges to the point that when compared graphically against film in figures 5c and 5d, digital's graphic depiction is virtually nonexistent.

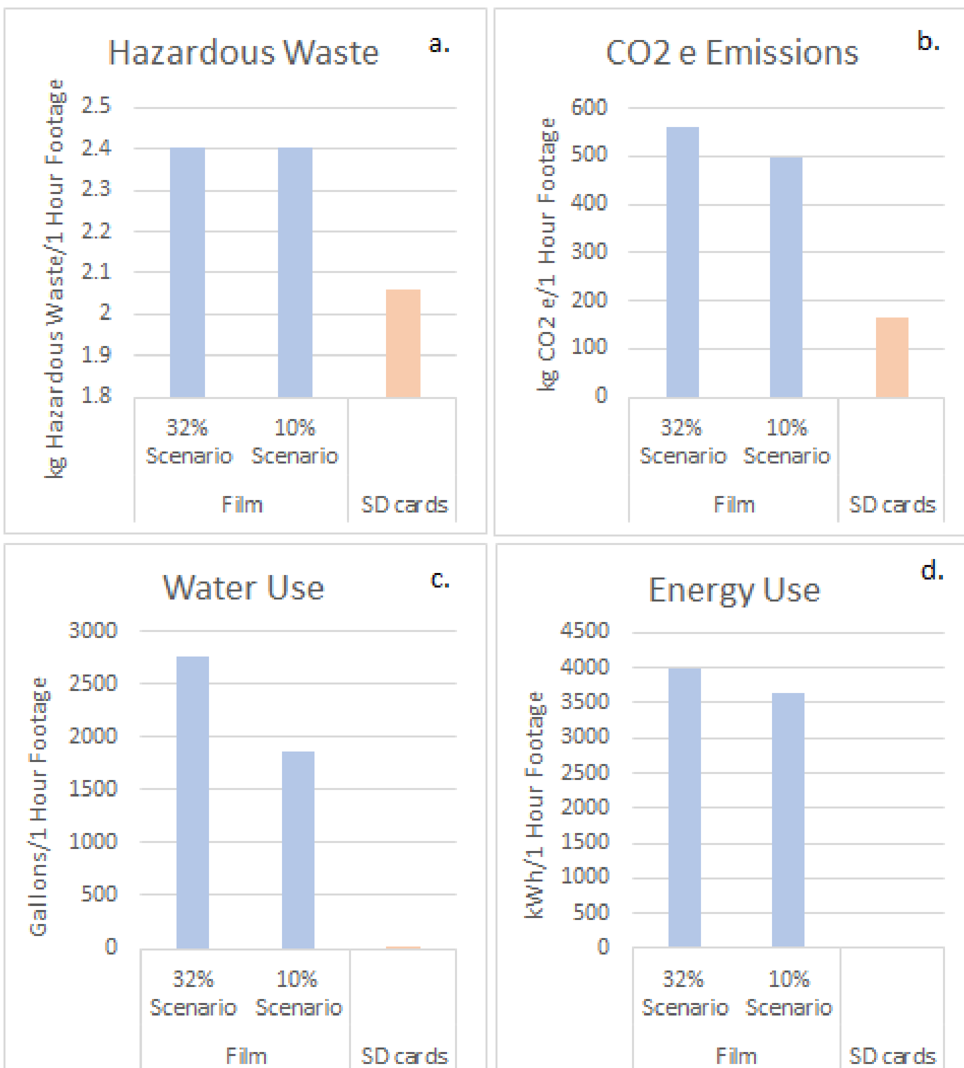

Figure 5: Bar graphs comparing original film impact values, values adjusted for 10% silver mining, and SD card values for each environmental metric: hazardous waste (a.), CO_2e (b.), water (c.), and energy (d.).

Two additional values that were particularly uncertain for film were the emulsion layer chemical and cellulose acetate base chemical prices. Estimates for these product prices values were used to convert the EPA EEIO values, given in "impact per 2013 USD ($) of product", into "impact per mass of product." Both the emulsion layers and the cellulose acetate base are made up of numerous chemicals that likely vary in price. Because we did not have access to the exact chemical mixtures used by Kodak, nor the cost they purchase those chemicals at, we approximated the price using each product's major chemical component by mass - gelatin for the emulsion layers, and cellulose acetate for the cellulose acetate base.

In our sensitivity analysis of these values, we adjusted our assumed price per kg of chemical up and down by 50%. Based on these adjustments, we arrived at the values seen in tables 4 and 5. Both tables show the net impacts for film across all stages considered: raw materials extraction, manufacturing, transportation, and development.

For cellulose acetate in table 4, changing the price up or down by 50% affects CO_2e emissions the most, resulting in a 6.77% change in total CO_2e emissions per hour of footage on film. Energy has the second highest effect, with a 4.24% change in kWh per hour of footage on film. Water and hazardous waste impacts are the smallest, changing by only 1.05% and 0.86%, respectively. In table 5, the impacts when we vary the price of the emulsion layers up and down by 50% are even smaller. The greatest impact occurs for CO_2e emissions, which change by 1.31%. All other impacts change by less than 1%.

These findings indicate that our uncertainty in the prices for the cellulose acetate base and emulsion layer chemicals should not have a substantial impact on our findings.

Impact of Emulsion Layers Price on Total Impacts per 1 Hour Footage					
Indicator	**Units**	**Current Value**	**-50% Scenario**	**+50% Scenario**	**% Change (+/-)**
Energy	**kWh/1 hr footage**	3989.71	3956.91	4022.51	0.82
Water	**gal/1 hr footage**	2761.10	2755.48	2766.71	0.20
CO_2e Emissions	**kg CO2/1 hr footage**	561.26	553.91	568.62	1.31
Hazardous Waste	**kg waste/1 hr footage**	2.41	2.40	2.41	0.11

Table 4: Table summarizing the results of 50% impact increase and reduction scenarios for the impact of emulsion layer price on total film values.

Impact of Cellulose Acetate Price on Total Impacts per 1 Hour Footage					
Indicator	**Units**	**Current Value**	**-50% Scenario**	**+50% Scenario**	**Change (%+/-)**
Energy	**kWh/1 hr footage**	3989.71	3820.37	4159.04	4.24
Water	**gal/1 hr footage**	2761.10	2732.10	2790.09	1.05
CO_2e Emissions	**kg CO2/1 hr footage**	561.26	523.29	599.23	6.77
Hazardous Waste	**kg waste/1 hr footage**	2.41	2.38	2.43	0.86

Table 5: Table summarizing the results of 50% impact increase and reduction scenarios for the impact of cellulose acetate price in film development.

Impact of Film Development on Total Impacts per 1 Hour Footage						
Indicator	**Units**	**Current Value**	**-10% Scenario**	**-25% Scenario**	**-50% Scenario**	**-75% scenario**
Energy	**kWh/1 hr footage**	2763.28	2486.95	2072.46	1381.64	690.82
Water	**gal/1 hr footage**	942.69	848.42	707.02	471.34	235.67
CO_2e Emissions	**kg/1 hr footage**	106.23	95.60	79.67	53.11	26.56
Hazardous Waste	**kg/1 hr footage**	0.56	0.51	0.42	0.28	0.25

Table 6: Table summarizing the results of 10%, 25%, 50%, and 75% impact reduction scenarios for the film development metrics of one hour of footage.

In the absence of recent research on cinematic film development, we relied on outdated and ill-suited resources for our development values that may have overestimated the impacts for this section. Our sensitivity analysis in this section aims to account for the discrepancy that may have occurred due to an assumption of linear correlation between resources required for one still-frame exposure versus thousands of feet of motion picture exposures. We compared our current values to a series of reduction scenarios, shown in table 6 (-10%, -25%, -50%, and -75%). Additionally, we compared the reduction scenario development values to the net impacts for digital SD cards to assess the remaining disparity in impacts after accounting for overestimation of development values.

For energy, we anticipate that the true impact falls somewhere between the current estimate of 2763.28 kWh and the 50% reduction scenario value of 1381.64 kWh per hour of editable footage. However, even under the 75% reduction scenario, development was still roughly 31 times as energy intensive as all of the stages of digital combined. This implies that there is virtually no chance that film can reduce its resource use in terms of energy consumption to ever reach a level comparable to digital.

Similarly for water use, we anticipate the true impact to fall within the range between the current estimate of 942.69 gallons and the 50% reduction scenario value of 471.34 gallons. However, even a 75% reduction in use would result in 471.34 gallons per hour of editable footage on film, which is 38 times higher than all digital water use. This further emphasizes that film development is resource intensive to an extent that can never be improved to match the efficiency of digital SD cards.

We anticipate that the true CO_2e emissions impact falls between the current estimate of 106.23 kg CO_2e and the 25% reduction scenario value of 79.67 kg CO_2e per hour of footage on film for development. For this indicator, values for development are on the same scale as those for the entire digital LCA, and therefore we can focus on how much the values could change based on the possibility that these values are inaccurate.

Finally, looking at hazardous waste this value is again within our anticipated range and therefore we can focus on accuracy of values. For this indicator, we anticipate that the true impact falls between the current estimate of 0.56 kg and the 25% reduction scenario value of 0.42 kg hazardous waste per hour of editable footage on film for development.

Overall, the fact that development values can be reduced so dramatically and remain on-par with, if not substantially greater than, net development impacts indicates that regardless of potential overestimation for development values, the environmental impacts of capturing footage on film are substantially greater than those of capturing footage on digital SD card.

Digital

The current values for semiconductor chips were found from existing literature. For energy and water, we used data from *The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices,* an LCA report that provided the total impact values for semiconductor chips while excluding use phase impacts. CO_2e emissions and hazardous waste values were found in *Seagate Koho Enterprise Solid-State Drive Product Life Cycle Assessment Summary* and *Nytro 1551 Sustainability Report*, two reports on LCA of SSD, which are extremely similar in composition to SD cards according to UCLA's Professor Gupta. These sources took into account raw materials and manufacturing impacts which we are confident in, but likely underestimated the impacts of purification across all four indicators. To incorporate these unaccounted purification impacts, we compared our current estimates to a series of increase scenarios in table 7(+10%, +20%, and +50%).

None of the increase scenarios changed the impact values drastically, and all remain magnitudes below the corresponding values for film manufacturing. The indicator that was impacted the least was hazardous waste, increasing by only 0.33 kg/hour of footage. CO_2e emissions changed most drastically, increasing by 45.64 kg/hour of footage. These differences indicate that the current values we have for semiconductor chips are fairly representative of the true values. This is what we expected since purification was the only stage that lacked comprehensive data in the LCAs values.

Impact of Purification on Total Impacts per 1 Hour Footage					
Indicator	**Units**	**Current Value**	**10% Scenario**	**20% Scenario**	**50% Scenario**
Energy	**kWh/1 hr footage**	22.15	24.36	26.58	33.22
Water	**gal/1 hr footage**	12.34	13.58	14.81	18.52
CO_2e Emissions	**kg/1 hr footage**	90.76	102.22	111.52	139.4
Hazardous Waste	**kg/1 hr footage**	1.62	1.79	1.95	1.95

Table 7: Table summarizing the results of 10%, 20%, and 50% impact increase scenarios for material purification in digital semiconductor development.

A sensitivity analysis was also conducted on the energy and water use impacts of plastic production for SD card casing. Energy and water are highlighted in this sensitivity analysis because no SD card LCAs accounted for these indicators, meaning we had to rely on general energy and water values per kg of plastic production and apply those to the weight of the SD card casing. Since we do not know if these general plastic production impacts are under or overestimates of SD card casing impacts, we considered both % increase and % reduction scenarios to determine the lower and upper bounds of our uncertainty. CO_2e and hazardous waste values for SD card casing were accounted for in SD card LCAs, so we are confident in those values and did not need to include them in this sensitivity analysis.

For all the scenarios shown in table 8, the differences in water and energy impacts for SD card casing between these scenarios are several orders of magnitude smaller than the current total estimates for SD manufacturing overall (12.34gal/hour of footage and 22.15kWh/hour of footage). Due to these very small differences, the current values for SD card casing can be assumed to be representative of the true values.

Impact of Plastic Production on SD Card Casing Impacts								
Indicator	Units	-50% Scenario	-20% Scenario	-10% Scenario	Current Value	+10% Scenario	+20% Scenario	+50% Scenario
Energy	**kWh/1 hr footage**	0.013	0.02	0.023	0.025	0.028	0.03	0.038
Water	**gal/1 hr footage**	0.024	0.039	0.044	0.049	0.053	0.058	0.073

Table 8: Table summarizing the results of 10%, 20%, and 50% impact increase and reduction scenarios for plastic production in SD card manufacturing.

Discussion

Interpretation

Our study found that capturing one hour of footage on 35mm film as opposed to on a single 1TB SD card has substantially greater environmental impacts in terms of energy use and water use. While the difference was less drastic for the remaining two categories, capturing footage on film also generated more CO_2e emissions and released more hazardous waste into the environment. These findings support our hypothesis that analog film would have greater environmental impacts than its digital counterpart, but at a greater magnitude than we had anticipated.

For 35mm film, we considered all of the inputs — silver, emulsion chemicals, cellulose acetate base chemicals, development chemicals, manufacturing and development energy and water demands, etc.— required to make 5400 feet of film, the full length needed to store an hour of footage shot at 24 fps. On the digital side, we considered all of the inputs— copper, resin epoxy, quartz, manufacturing energy and water demands, etc.— required to make a single semiconductor memory chip with 1TB of storage, of which HBO stores one hour of footage at a time, but reuses numerous times over the course of its lifespan. While analog film has exponentially greater environmental impacts than digital *per hour of footage*, if one were to consider the *mass* of physical material needed to store an hour of footage on film versus digital memory card, the impact *per physical material output* would be much more comparable.

One cannot capture a single frame of footage digitally without a complete semiconductor chip, but one can hypothetically capture a single frame of footage with approximately 0.75 inches of 35mm film stock. Thus, there is a threshold number of frames where the environmental impacts of film and digital intersect. This break-even point means that a specific number of frames must be captured on an SD card before it is a more environmentally friendly option. Based on our results for an hour of 35mm film media in each impact category, the impacts per frame for film are approximately as follows:

- 0.05 kWh of energy per frame,
- 0.03 gallons of water per frame,
- 0.006 kg CO_2e per frame, and
- 0.00002 kg of waste per frame.

This means that the break-even point for the impacts of film and digital occurs at approximately 443 frames for energy use, 411 frames for water use, 27811 frames for CO_2e emissions, and 81000 frames for hazardous waste releases, which translates to around 27.6 ft, 25.7 ft, 1738 ft, and 5062.5 ft of film, respectively. Therefore, it is more sustainable to shoot on film than digital in all impact categories for any length of film below 25 ft. However, this translates to only 411 frames, or 17 seconds at 24 fps. Due to the fact the smallest roll of 35mm film sold by Kodak is 100 feet, there would be no scenario where film's total impacts can be limited to those of 25 ft of film (The Essential Reference Guide for Filmmakers). Therefore, it is ultimately more sustainable for footage to be shot on digital than on film across all impact categories for any amount of footage greater than 81000 frames, which translates to 3375 seconds or 56 minutes at 24 fps.

Furthermore, our results likely severely overestimate the environmental impacts for digital since we considered the impacts of a single SD card capable of storing at least one hour of footage *without* accounting for how many times that SD card may be reused over its lifespan. Had we distributed these impacts across the likely innumerable hours of footage shot on a SD card over its lifespan, our impacts per 1 hour of footage for digital would be a fraction of their current values.

Limitations

The nature of this study, as a six-month independent student review, meant that we had limited access to proprietary information from companies manufacturing these products and that LCA industry standard data compilations were beyond our financial resources. As such, the bulk of our data collection relied on literature available through UCLA's library or made public by the EPA. Some of this data was averaged across industries or economic sectors, meaning it may not accurately reflect the impacts of the specific processes considered here.

While several comprehensive LCAs have been conducted in the past for semiconductor chips, we did not find sufficient existing LCA research on cinematic 35mm film. Research with direct access to Kodak, as the primary producer of motion picture film in the United States, would substantially improve available information on the environmental impacts of film manufacturing.

Though more LCA literature was available for SD cards, the sources used were published between 1990-2020 and some integral values from older sources had not been updated with new research. Because the semiconductor industry is rapidly changing, some of the values in our calculations may not accurately reflect the impacts of current semiconductor technology. This acts as a limitation as the values we collected cannot necessarily stand the test of time and will only become more inaccurate as semiconductor manufacturing improves.

Given the limitations discussed above, our Excel tool should not be utilized as a definitive measure of the impacts of film and semiconductors, but rather should be viewed as an educational tool building on existing research in this field.

Moving Forward

Across the four selected environmental impact indicators of energy, water, CO_2e, and hazardous waste, an hour of footage captured on digital SD cards overwhelmingly outperformed an hour of footage captured on traditional analog film. Sensitivity testing helped build confidence in these results, though specific values may be unreliable. We hope that this report and our excel tool will enable more filmmakers to confront the environmental implications of their media selection and encourage informed decision-making. Additionally, our work serves as an indication of where further comprehensive research is required.

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