Yupana: Understanding the Environmental Impact of Digital Fabrication Prototyping through a Life Cycle Impact Assessment

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Abstract

Participating in creative processes, such as digital fabrication, involves a range of decisions—from material choices to disposal—that can change the environmental implications. Although often overlooked in sustainability discussions, digital fabrication prototyping can contribute to waste, CO_2 emissions, and energy consumption. To address this, we developed Yupana, a LCA calculator for digital fabrication supported by a comprehensive Life Cycle Impact Assessment (LCIA). Yupana evaluates a physical prototype's environmental impact across its entire life: raw materials processing, transportation, digital fabrication, and end-of-life. Yupana's interface visually compares energy consumption and CO_2 emissions per phase, suggesting sustainable alternatives for informed decision-making. Findings from interviews with 13 experts suggest that a life cycle approach not only clarifies how decisions in each phase collectively influence a prototype's overall environmental impact but also enables participants to compare and discern the environmental contributions of individual decisions per phase. Yupana serves as a tool to enable conversations around sustainable making, supporting informed decisions in digital fabrication prototyping.

Introduction

Creative processes, particularly within digital fabrication, involve a thoughtful consideration of sustainability at each stage of the life cycle of a prototype. Individuals participating in these processes often face decisions with environmental implications such as material choices, energy consumption during digital fabrication, and considerations towards the end-of-life of their creations. Thus, a broader understanding of the environmental impact of their practice could lead to a shift toward sustainable choices and minimizing environmental footprints in the pursuit of innovation. Sustainability in Human-Computer Interaction (SHCI) has sparked extensive discussions within the HCI community [11, 14, 17, 33]. Researchers have explored various approaches such as Sustainable Making [31], Sustainable Interaction Design (SID) [5, 25], Materializing Sustainability [36, 37] and Design for Repair [32]. Expanding on Sustainable Making, our focus narrows down to physical prototyping within the realm of digital fabrication. Digital fabrication is a broadly used method, not only in HCI but also broader maker communities, for designing and producing interactive prototypes, tangible interfaces, and physical artifacts. In this context, design approaches such as the use of a Sustainable Prototyping Life Cycle (SPLC) [23], design for waste reduction [9, 10, 39], design with reused materials [18, 40], prototype with biomaterials [4, 15, 28, 34, 35], or reuse and re-purpose of electronics [21, 24, 41] at prototyping time has further motivated this work. Adding to existing effort of makers, designers and HCI researchers for more sustainable making, we contribute with a holistic understanding of the overall environmental impact of digital fabrication prototyping. Instead of focusing on individual aspects such as material choice or end-of-life decisions, we analyze the environmental impact across each phase of a prototype life cycle.

Life Cycle Assessment (LCA) [1] is a well-established sustainability method that evaluates environmental impacts across all life cycle stages. While widely used in product design, construction, energy, waste management, and transportation, its application in HCI is still emerging [42, 43]. LCA involves four steps [13]: defining goals and scope, compiling a life cycle inventory (LCI), conducting a life cycle impact assessment (LCIA), and interpreting results. The LCI provides essential data for estimating energy use and CO_2 emissions, a quicker first step than completing the full LCA. We adopted this approach, using LCI data as input for the LCIA methodology that forms the basis of our LCA calculator for digital fabrication prototyping, Yupana.

This paper introduces Yupana, an open-source tool for estimating energy consumption and CO_2 emissions in digital fabrication prototyping. Beyond quantitative assessment, Yupana fosters dialogue about sustainable making among digital fabrication practitioners. We envision it as a way to empower users to make more informed, sustainable decisions during prototyping. Our contributions include:

1. The development of Yupana as the first open-source LCA calculator for digital fabrication prototypes, integrating trusted LCA data to estimate environmental impacts of 3D printing and laser-cutting.
2. A visualization feature that compares environmental impacts across different life cycle phases, including raw

material processing, transportation, digital fabrication, and end-of-life. This helps users understand how prototyping decisions affect sustainability.
3. A discussion of interview findings on Yupana’s role in supporting sustainable making practices and its potential to promote more sustainable digital fabrication.

Related Work

In the realm of sustainability, calculators are tools that have been used for evaluating environmental footprints [8], contributing not only to personal footprint assessment but also playing a crucial role in education and awareness [6]. These tools have been designed to estimate individual contributions, fostering carbon emission reductions through informed behavior change. A comprehensive review of ecological footprint calculators has revealed their direct and indirect impact on enhancing students’ knowledge and understanding of environmental sustainability, showcasing their potential as educational instruments [7, 19]. With these compelling affirmations emphasizing calculators as invaluable instruments for offering a comprehensive perspective on environmental impact and fostering more informed decision-making, we chose to model Yupana as a calculator.

Diverse approaches to sustainability have emerged within the design and maker communities. Kohtala’s research [22] explores the maker community’s understanding of sustainability, while other studies assess the environmental impacts of additive (3D printing) and subtractive (laser cutting) manufacturing [12, 27]. Moreover, other works on sustainable materials for 3D printing [26, 30] provide alternatives for environmentally conscious choices in digital fabrication. Engineering perspectives, especially in manufacturing and mechanical engineering [43], have approached sustainability by assessing the energy and efficiency of laser cutting [20] and 3D printing processes [3, 29, 38]. We made use of these life cycle assessment reports to generate the input data running in Yupana’s calculations.

Besides multiple efforts at sustainable making in digital fabrication, there is still a gap in existing calculators when it comes to comprehensively understanding the environmental impact of digital fabrication. Inspired by these diverse sustainable-making approaches, Yupana serves as a dual-purpose tool—quantifying environmental impact and sparking sustainability dialogues within the maker and HCI communities. It drives collective efforts toward more sustainable-making practices, aiming to open conversations and support informed decision-making in the realm of digital fabrication prototyping.

Yupana is an online tool that: a) estimates the environmental impacts of a prototype per phase, b) compares the impacts of different prototyping materials and techniques, c) provides information ab out the user’s choices, and d) gives sustainability suggestions to guide potential changes in the user’s initial decisions. The calculations made per life phase of a prototype and more information on how to use this tool can be found at: https://github.com/EldyLazaro/YUPANA

The Yupana Approach

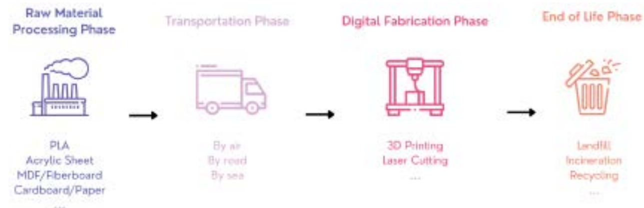

Fig. 1. The entire life cycle of a prototype involves raw material processing, transportation, digital fabrication, and end of life

Input and interaction: Yupana’s interface, illustrated in Figure (2), guides users through the digital fabrication process. Users select the fabrication type (3D printing or laser cutting) and provide information in each prototyping phase (raw material processing, transportation, digital fabrication, and prototype disposal). The input data section (Figure 2a) is organized by the LCA phases, and user can make selections accordingly that phase such as selecting materials used on raw material phase or specifying shipping distances. After completing all inputs, users click "calculate," and Yupana estimates the environmental impact based on the provided job information.

Visualizations: Results are presented through bar charts and job history tables on the right side of the interface (Figure 2b), showcasing energy consumption and CO_2 emissions per phase per job.

Environmental Impact Information: Yupana features an "i" symbol next to each data input field (Figure 2c), providing detailed information about the environmental impact associated with the user’s choices. The "i" symbol is displayed in black for choices with only pros and in red for selections with cons, including percentages of impact compared to other options and an explanation of the input’s importance for the calculation.

Sustainability Suggestions: The tool generates sustainability suggestions in the right corner of each phase section (’!’) (Figure 2d). Displayed in red when there are suggestions for more sustainable choices. If user clicks on the sign, it displays these recommendations to reduce their impact or use them for future decision-making.

User Study: Experts Interviews

We interviewed 13 members (I1-I13) of digital fabrication labs to collect their feedback about Yupana’s usability, their perception when evaluated their own works and new, and clarifying information on their practice. All of our participants actively prototype in their labs, take decisions about material and machine purchases, or have a direct influence in such decisions making. The interviewees were asked to provide one-month job history report or up to five .STL files of a project previously prototyped in the lab. They were asked to deliver this information up to one day before the interview. We input all that data into Yupana in preparation to the interview.

Protocol

The 60-minute interviews were through video conference, they were video, and audio recorded and they were transcribed after. The participation was voluntary without monetary compensation. All interviews were conducted by the same interviewer. The interview protocol consisted of three parts, (A) a pre-questionnaire, (B) Yupana user-interaction, and (C) a post-questionnaire.

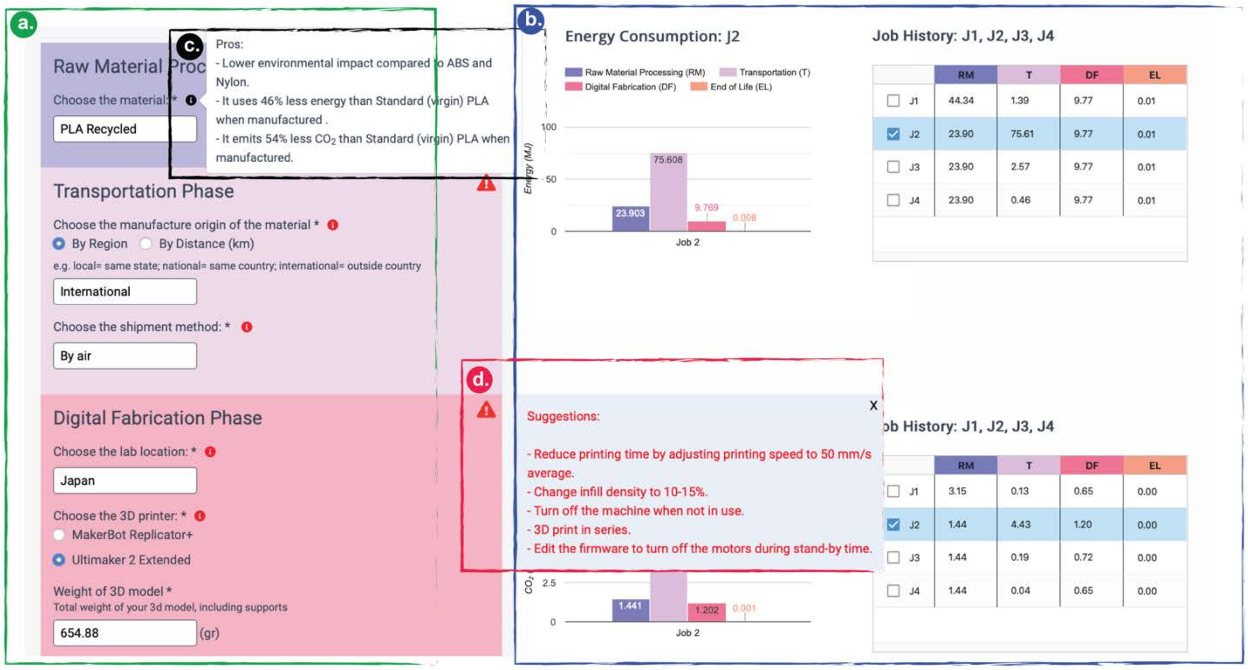

Fig. 2. Yupana Interface. a) User input data, b) bar charts and job history tables showing the energy consumption and CO_2 emissions, c)learning information, and d)sustainability suggestions.

A. Pre-questionnaire. (10 minutes) We used open-ended questions to learn about interviewees' roles in their labs, and the knowledge they have about environmental impact and LCA. Based on their answers, the interviewer presented a diagram of a prototype's life cycle which included fours phases. The participants were asked to rate the phases in order of what they think to have the highest or lowest energy consumption and CO_2 emissions.

B. Yupana user-interaction. (30 minutes) The interviewer shared her screen and showed how to interact with the tool while presenting the energy and CO_2 emissions diagnosis made with the interviewees' own prototyping reports. The interviewer explained in detail the parts of the interface, and the type of information Yupana provides. The interviewer gave remote mouse control to the participants to interact with the tool. The interviewees were asked to interact with Yupana following a set of tasks until they got familiar with the interface. After that, the interviewer requested the participants to review the bar charts, the tables, the information provided in the sustainability suggestions ("!"), and information pop-ups ("i") to understand the comparison between digital fabrication jobs and simulate other set of choices.

C. Post-questionnaire. (20 minutes) Interviewees answered questions such as the lessons learned using Yupana, their perception about their current environmental impact, the changes they could consider feasible to make in their labs, changes they would be ready to do now, and changes that will take more time to make. Finally, we asked them for their feedback about Yupana's interface.

Findings

The findings show participants' views of their environmental impact when are analyzed per LCA phase. Themes include the participant's perceptions of the tool, the feasibility of implementing a more sustainable approach, and the lessons learned.

A) Perceptions of their current impact of Digital Fabrication. Participants perceived the digital fabrication phase as having the highest energy consumption, primarily due to continuous machine operation, while transportation was seen as the phase with the highest CO_2 emissions, influenced by the distance materials travel.

I1: "We leave the 3D printers printing all night and we do not turn them off until the next day when we are back in the lab. I think they are probably using unnecessary energy."

I2: "The materials we use are not manufactured in our country; we buy them from overseas."

I8: "We have the laser cutter running all day [during certain events]."

B) Feasibility of Changes in Different Phases. Nine participants expressed that implementing changes in the digital fabrication phase, especially related to energy-efficient machines, would take time, as they do not frequently update equipment. Acquiring locally manufactured or recycled materials was expected to be a gradual process over the next few years.

I1: "Buying energy-efficient machines is definitely something we will think about the next time we buy machines." I4: "It is more difficult to take action in the Digital Fabrication phase because we don't renew equipment every year."

Participants believed that changes in the raw material phase, such as purchasing recycled PLA, and improvements in transportation by seeking local providers and reducing travel distances, were feasible. However, adjustments in the end-of-life phase were viewed as challenging, with uncertainty about waste disposal practices in each institution.

I3: "I see it feasible to purchase different raw materials (recycled PLA). I will also look for the information about where the materials are coming from, but I cannot do so much about the end-of-life phase because I am not sure what happens with my waste after I throw it away."

I4: "I think changes in the raw material phase are feasible to make, I have to check on price and environmental impact. Regarding the transportation phase, buying locally is a decision we can make but the change will depend on availability. Improvements in the fabrication phase would be more difficult to make. About the end-of-life phase, I honestly don't know what happens behind the scenes after I throw away my waste. We would like to know what our company offers about it."

C) Perceptions of Environment Impact through LCIA. Post-questionnaire responses highlighted that participants were initially unaware of the distribution of energy consumption and CO_2 emissions across phases. Yupana changed their perspective, revealing unexpected impacts in the transportation and digital fabrication phases. Participants expressed a newfound awareness and the tool's potential to guide better decision-making in each phase.

I6: "Seeing the magnitude of how much worse the raw material energy usage is versus transportation was definitely helpful, and I thought that was actually very interesting."

I3: "I have learned that the CO_2 emissions in the Digital Fabrication phase could change depending on the country my object is prototyped. For instance, I have learned that 3D printing my object in the USA generates less CO_2 emissions than doing it in Germany. The sustainability suggestions have useful information that explains the differences of the impact outcomes."

I8: "This tool has raised awareness that leads to action. I feel I can make better decisions in each phase thinking about our environmental impact."

Discussion

Yupana emerges as a tool that provides participants with nuanced insights into the environmental impact of digital fabrication. This discussion explores Yupana's life cycle approach and the opportunities it presents for sustainable practices in digital fabrication prototyping drawn from participants' engagement with the tool, and the implications of Yupana's interface at supporting sustainability conversations in Digital Fabrication prototyping.

a) Yupana's Life Cycle Approach: Opportunities for Sustainable Prototyping Practices

The findings in the interview showed that Yupana's interface organized in phases stimulates discussions and aids informed decision-making in digital fabrication. Conversations about raw materials indicated a shift towards sustain-ability, as participants expressed a willingness to transition, for instance, from virgin to recycled PLA in 3D printing. To concretize this commitment, we would recommend establishing dedicated networks that directly connect practitioners with verified sustainable suppliers. Additionally, fostering a culture of active information exchange within the digital fabrication community can play a pivotal role in facilitating a smoother transition toward more sustainable material alternatives. Initiatives, such as online platforms, specifically designed for sharing insights and resources, could serve as practical starting points in this endeavor. The use of Yupana also offered insights into participants' considerations regarding the environmental impact of international air shipping compared to other combinations of transportation modes and distances within a prototype's life cycle. To address these considerations, practitioners have opportunities to advocate for lower-impact supply chains by initiating conversations with material suppliers and actively pursuing locally sourced and manufactured materials. Collaborative efforts within the digital fabrication community, such as reducing shipping distances and adopting carbon-neutral goals, provide concrete avenues to minimize the overall carbon footprint of this phase. Participants expressed a lack of knowledge about the energy sources powering machines in their labs, indicating a perceived limited control over the environmental outcomes of the digital fabrication phase. We can see this raise in awareness as an opportunity for systemic changes, where practitioners, could advocate for increased transparency and knowledge-sharing with their respective institutions. Furthermore, the participants' interest in acquiring energy-efficient machines and creating protocols for machining presents an additional opportunity for collaboration within the digital fabrication community to establish best practices that further optimize energy efficiency, emphasizing a collective effort towards a more environmentally sustainable approach in digital fabrication prototyping. Participants expressed their concerns about uncertainties in waste disposal practices during the end-of-life phase of a prototype. They expressed a desire for more information and control over the fate of their waste. This presents an opportunity for institutions where these labs are hosted to take a proactive role in shaping policies for proper waste management. Establishing partnerships between labs and recycling facilities, providing in-lab clear guidelines for proper disposal methods, and conducting awareness campaigns on specific concerns and contribute to a more responsible waste disposal approach.

Certainly, we attempted to outline the multiple opportunities branching from the discussions we had with digital fabrication experts by formulating a table of actionable items (see Table 1). These actions are categorized per phase of a prototype's life cycle and by actor, recognizing that the proposed opportunities rely on the support of crucial roles within the lab community. The actors identified include designer, lab manager, and institution.

	DESIGNER	LAB MANAGER	INSTITUTION
RAW MATERIAL PROCESSING PHASE	Choose a material that is made of recycled materials (e.g. recycled cardboard, recycled PLA)	Provide materials that are made of recycled materials (e.g. recycled cardboard, recycled PLA)	- Make prototyping materials available in the library store on campus that use clean renewable source (wind, solar energy) to be manufactured. - Support initiatives related to sustainability or zero waste.
	Choose a material that has a low embodied energy (see Fig. 2a)	Provide materials that have a low embodied energy. (see Fig. 2a)	
	Choose a material that does not have toxic additives on its composition (review the material's data sheet)	Provide materials that do not use toxic additives on its fabrication process (review the material's data sheet)	
	Choose a material that is locally sourced and manufactured	Provide materials that use locally sourced raw materials	
	Choose a material that uses clean renewable source (e.g. wind, solar energy) to be manufactured	Provide materials that use clean renewable source (wind, solar energy) to be manufactured.	
	Choose a material that has an Energy Star and Cradle to Cradle certification	Provide materials and machine that are Energy Star certified and Cradle to Cradle certified.	
	Choose a material that is recycled everywhere.	Provide materials that are recycled everywhere.	
	Follow the lab's guideline to make a purchase list	Make a guideline of recommended materials, electronic components and equipment to use in the lab.	
TRANSPORTA-TION PHASE	Plan ahead of time and reduce the number of visits to the local store	Identify and purchase materials that are locally manufactured.	- Make available resources in the institution that allows to apply for grants that could support the use of machines and materials with environmental certification (safe in manufacturing and use). - Take a major step forward in securing affordable renewable energy for the campus.
	Make your list of materials from the same store, preferably from a locally manufactured store	Ship the materials by ocean preferably or by road. Avoid airplane delivery (see Fig. 2b).	
	Use Eco-friendly transportation methods to pick up materials (e.g. bicycle, electric/hybrid vehicles, public transportation)	Use Eco-friendly shipping (e.g. The SmartWay Transport Partnership in the USA, Inland Barges or biodiesel trucking)	
		Purchase machines that have energy efficient certification such as Energy Star	
DIGITAL FABRICATION PHASE	Use scraps and leftovers for the first prototype iterations	Set up a storage area and divide it by embody energy of materials and potential use.	- Stablish policies on campus tha lead to a more sustainable life style. For example, single-use plastic elimination policy. - Acomplish Global Sustainable Goals to support future projects and grants.
	Use the optimal parameters assigned for each material and machine in the lab	Label materials with recycling codes to identify materials for their sustainable properties.	
	Avoid the use of glues, or only use the ones that are easily soluble or heat reversible	Provide the lab with glues, or only use the ones that are easily soluble or heat reversible.	
	Avoid combinations of materials that are difficult to separate for recycling (e.g. cardboard and acrylic sheet)	Create and save configurations in the machines with efficient parameters for each materials and machine to reduce energy consumption and CO2 emissions. For example in 3D printing, adjust print speed, avoid heated bed if not necessary, proper orientation of the object to reduce supporting material, infill. For laser cutting, adjust the cutting speed per material to avoid double passes.	
	Save scraps and leftoversto for the next prototype following sustainable protocols	Create sustainable protocols for new materials following the previous guidelines set up by the lab in terms of storage and file configuration	
	Follow the sustainable protocols in each job	Use of alternative materials for 3D printing such as recycled PLA, or bio-composites for laser cutting.	
	Make the design easy to separate components that are hazardous, toxic, or not conventionally recyclable.	Create a step by step troubleshooting guideline to solve machining problems.	
		Make the technical documentation of the machines freely available or open-sourced with the lab	
END OF LIFE PHASE	Dispose the waste in the right trash bin following the protocols on how to recycle and dispose	Label disposal bins properly (landfill, recycling, compost, e-waste)	- The institution in the end of life phase could train the academic body in proper waste disposal and provide disposal facilities access on campus. - Ensure that every department and lab has separate disposal bins. - Improve disposal systems on campus (plastics, e-waste, recycling). - Provide visible instructions on campus on proper ways to dispose of equipment and supplies.
	Practice recover and recycling materials, for energy recover.	Design a protocol on how to recycle and dispose each material available in the lab to ensure proper disposal	

Table 1. Actionable Items for a Sustainable Prototyping Lab per actors and phases.

b) Implications of Yupana's Interface at Supporting Sustainability Conversation in Digital Fabrication

While our exploration of participants' perceptions of environmental impact through Yupana's interface hinted at its potential in promoting sustainability practices, its standout feature is adopting a life cycle approach organized by phases. This approach serves as a framework, fostering meaningful dialogues among practitioners and prompting discussions about the nuances of each phase in a prototype's life cycle. Yupana's structured visualization of environmental impact data encourages users to comprehend the relationship between multiple factors shaping the environmental outcomes in each phase. Its unique contribution lies in guiding users through a comprehensive understanding of life cycle phases—raw material processing, transportation, digital fabrication, and end-of-life—positioning Yupana as a tool for informed decision-making at every stage of prototyping. This holistic perspective enhances the efficacy of sustainability conversations, making them more nuanced and embedded in the specific context of digital fabrication.

Moreover, participants found Yupana's interface user-friendly, envisioning practical applications like informed material purchasing decisions and potential collaborative sustainability practices within the maker community. Sustainability suggestions and information pop-ups contribute to prompting improvements, extending Yupana's utility beyond environmental impact assessments. Participants agreed that Yupana provided enough information to understand the reasons behind a higher or lower environmental impact on a phase. For instance, Fig. 3 visually illustrates the impact of altering the transportation phase's shipping method, emphasizing specific recommendations for improvement, and providing users with insights into their practices. In conclusion, Yupana's positive evaluations suggest its influence on material choices, collaborative practices, and potential cost-effective decision-making.

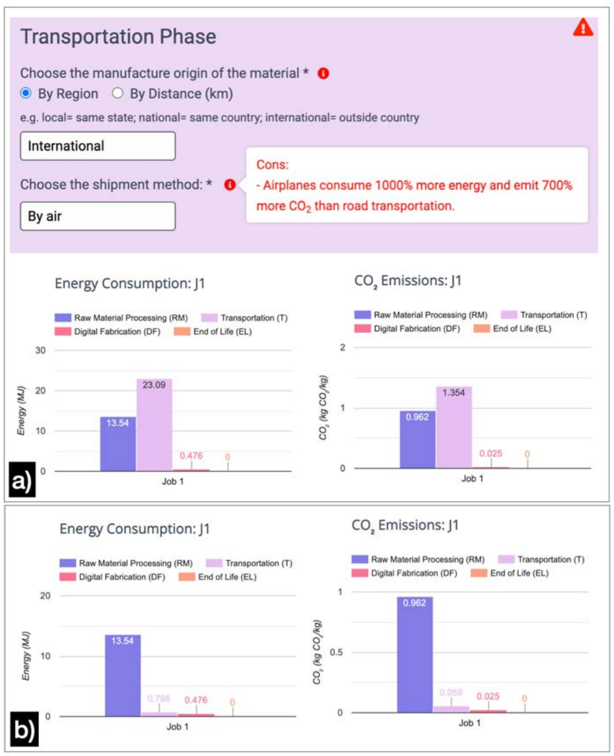

Fig. 3. Transportation phase ranks highest. Contrasting impacts of a) International air shipping vs b) National road shipping.

Conclusion

Our paper introduces Yupana, the first Life Cycle Assessment (LCA) calculator designed for digital fabrication. Yupana enhances the understanding of environmental impacts by visualizing data across the four key phases of digital fabrication prototyping (raw material processing, transportation, digital fabrication, and end of life). As an online, customizable, and open-source tool, it calculates and compares environmental impacts utilizing trusted LCA sources. The interface offers sustainability suggestions, impact information, graph comparisons, and detailed input data for each phase. Furthermore, the paper provides recommendations for sustainable practices tailored to different roles in digital fabrication prototyping in each phase. The experts' interviews show the perceptions on their own practice when visualizing the impact by phase, showcasing Yupana's potential as an informative tool for comprehending the impact of their prototypes and informing future sustainable decisions. We envision that Yupana could support the HCI community to reflect on the possibilities to improve their environmental footprint.

Future work involves enabling users to input their lab machines' details, usability evaluation, and expanding the calculator database to encompass a wider range of materials and machines. Interface enhancements will be role-specific, with lab managers gaining more control over features such as material types, shipping methods, machine parameters, and prototype end-of-life considerations. For students and designers, a simplified interface will aid decision-making. In response to user feedback, potential additions include an export button for downloading data and integration as a plug-in for software aiding file preparation. This integration could facilitate a graphical representation of job information alongside its environmental impact, enhancing usability.

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