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ENVIRONMENTAL IMPACTS OF 'LOOKS LIKE' PROTOTYPES: DOES KNOWING THE IMPACT ALTER STUDENTS FUTURE PRACTICE?

Louise R MANFREDI
Brown University, United States of America

ABSTRACT
Prototyping is fundamental to the design process, whether as a highly exploratory process in concept generation, as a communication tool with stakeholders and team members, or to refine a final concept. However, educators still perpetuate the use of permanent materials to make temporary artefacts. To understand this contradiction, reveal prototyping impact and student's perception of their process, a study was conducted across two undergraduate industrial design courses at Syracuse University which centred on circular economy and fast-track life cycle assessment implementation. In the first course, students produced 'looks like' prototypes of redesigned electronics for the circular economy. They were encouraged, not required, to use materials that could enter the recycling stream and to document their material flows: what was embodied in the prototype and what was wasted. A self-reflection on their prototyping process and impact on course content of their future practice was captured. In the second course, students produced groups of three replica prototypes differing only in material (e.g. cardboard, Bristol paper, foamboard) or production techniques (e.g. 3DP, CNC) for life cycle assessment (LCA).
Results indicated that providing students with knowledge on the environmental impacts of common prototyping material gave them more data to choose when materials should be used in their process, or whether they should be avoided entirely. This work adds to the growing literature on the need to both formally and informally teach design and engineering students to think critically about their own process and contribution to our collective impact as an industry.

Keywords: Sustainability, life cycle assessment, sentiment analysis, prototyping, material flows

1 INTRODUCTION
Industrial design is a prolific producer of models and prototypes using myriad material types with the goal of developing better solutions to human-centred design issues. Whilst accepted that this type of material consumption is part of the process and indeed important to student understanding and development of critical industrial design and design engineering skills [1], [2], [3] we tend to rely on materials that are suboptimal for the environment. Given that prototyping is a temporary step to a final solution, the use of permanent materials that go to landfill upon project completion is counter to the circular economy teachings that are now permeating the industrial design curriculum [4], [5].
Prototyping should follow the circular economic model for mass manufactured products and services [6]. At Syracuse University, research was undertaken to broadly understand and design interventions to increase compliance in recycling [7] and improve recovery of materials that were of value to the broader School of Design community [8], in essence cultivating internal circular behaviours. The studies illuminated the volumes and types of materials used, but did not perform life cycle assessments to quantify the overall environmental and human health impacts of design prototyping. There are student-accessible spreadsheets, books, and software add-ins (examples: [9], [10], [11]) to produce fast-track or quick LCAs, but the impact of prototype materials such as SLA resins, XPS foam, foam boards and specialty cardstocks are either behind database paywalls or detailed in high-level research papers. This paper aims to shed light on this knowledge deficit for students, educators and design practitioners.

2 METHODS
This paper explores the outcomes of two industrial design courses that were focused on different aspects of the circular economy and quantification of material impact in prototyping. The first was a product

systems course on redesigning products for the circular economy. The second was an independent study with six students investigating the impacts of commonly used materials for looks-like prototypes.

2.1 Products system course: Resigning for the circular economy

Eighteen students were tasked with redesigning common household appliances for the circular economy. Tasks included product teardowns, fully life cycle inventory analysis, and using either the Okala Practitioner [10] or IDEMAT [9] to strategize and propose designs with better environmental outcome [12]. Products varied from coffee makers to impact drivers and electric shavers and hairdryers. Students were supplied with materials that could readily enter the recycling stream such as various types of virgin and post-consumer cardboards and papers, paper adhesive tapes, and water-soluble glues. They were encouraged any material needed to use to product a looks-like prototype, but to consider the use of materials with lower global warming potential (GWP) where possible. They were also instructed to keep track of the materials used in the prototype and discarded in the design process. This was their first course introduction to circular economy, fast-track LCA, and product systems.

2.1.1 Data collection and analysis

Two data streams were collected and analysed post grade submission. The first was the material quantities used and discarded during the prototyping phase of the course. Discarded materials were subclassified as landfill, recycle stream, or having reuse potential and aggregated across projects.
A 500-word reflection was required to assess barriers to model making using planar recyclable materials, and secondly to determine if the course content might prompt them to think differently about design and the environment. The questions were: (1) *You were encouraged to use materials for prototyping that could be recycled within the building. Describe your experience with this process and how rigidly you tried to follow the suggestion*, and (2) *Design for sustainability is gaining traction across many industries. Describe what elements of the course, if any, you would like to embed into your own design practices moving forward*. Sentiment analysis was conducted using Text iQ in Qualtrics, a survey software, and verified manually. Inductive coding was used to identify themes across the responses.

2.2 Group independent study: Global warming potential of prototyping materials

In the following semester, an independent study was initiated with six students centred on measuring material impacts. Students selected two common household products and produced six prototypes each (task lamp, SLR camera, 750ml spray bottle, Bluetooth speaker, remote control, allergy medicine dispenser and a keyboard vacuum cleaner). One product was reproduced as a mono-material looks-like prototype from sheet materials and processed manually, the second from materials used in additive or subtractive machine-based operation, such as 3DP and CNC milling. The purpose of the study was to compare global warming potential for similar looks-like prototypes across material types within the production method – manual or machine.

2.2.1 Data collection and analysis

Material used and wasted was recorded in a spreadsheet in grams converted to kilograms for material impact to be calculated per prototype. A simple LCA was calculated with Carbon Graph software [13] using the ReCiPe 2016 v1.03 midpoint characterisation model. The system boundary did not encompass transportation, depreciation of equipment or model making consumables, thus the LCA was focused on the global warming potential of the material embodied in the prototype and in the waste produced.

3 RESULTS AND DISCUSSION

3.1 Product system course

Fourteen completed material flows spreadsheets were aggregated revealing that the majority of materials, based solely on reported mass, were suitable for the recycling stream in the county (

*Figure **1***). A small number of students (n=2) used 3D printing for some of their prototype and some used materials from a recently installed departmental material exchange [8] for functional or representational reasons (n=3). Almost 50% of materials used were embodied in the final prototype, the remainder going to the material exchange/reuse stream (33%), recycling stream (13%) and lastly landfill (4%). The behaviour of channelling useful materials aligned with previous findings that adequate signage and instruction leads to reduce landfill waste produced in the design studio [7]. It was also observed that students favoured post-consumer (pC) single and double ply cardboard to their virgin counterparts (see *Figure* **2**A-C for prototype examples). The pC cardboard was collected by the instructor from packing boxes that came in to the school multiple weeks prior. Lessons on post-consumer impact scores could have prompted this trend, as students were unaware that impact during manufacturing is not calculated in reuse of a material if not reprocessed, such as cardboard and paper being pulped and reformed.

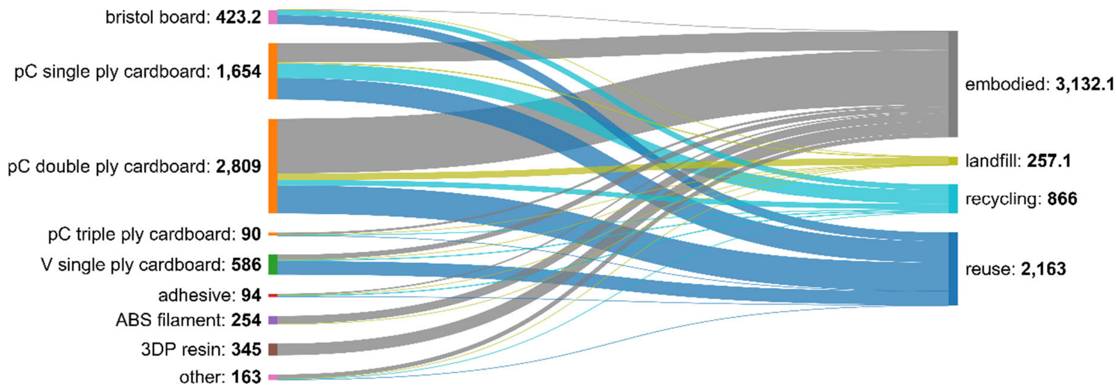

Figure 1. Sankey diagram of material flows in the prototyping process (g)

Sentiment analysis and initial coding was performed using sixteen completed reflections (two were discarded for not answering the questions given). When asked to describe their experience using recyclable, mixed sentiment was mostly observed (*Table **1***). While for many students here was consensus that thinking about impacts and waste generation was important, a skill deficit was identified in manipulating card and paper to create curvilinear surface representations. Students did indicate that they were acquiring new knowledge during the prototyping phase and were thinking about their environmental impacts beyond the course.

Table 1. Initial sentiment and coding analysis from the 500-word reflections

Question	Sentiment	Emerging themes	Verbatim quotes
Describe your experience with this process and how rigidly you tried to follow the suggestion.	3 negatives 12 mixed 1 positive	○ Difficulty with the materials ○ Lack of impact knowledge ○ Prototype skills deficit ○ Positive challenge ○ Discovery of new knowledge	*"Cardboard is fairly rigid and hard to use when trying to create organic shapes"* *"I couldn't help but think about the environmental impact of prototypes not just for this class but for other classes as well."* *"With nonrecyclable prototyping materials, there is much more control, and it is easier to get a more high- fidelity finish."* *"I do think this is something I will continue to employ in future prototyping."* *"I never knew about LCA prior to this class."*
Describe what elements of the course, if any, you would like to embed into your own design practices moving forward.	6 mixed 10 positives	○ Need more research ○ Perspective change ○ Implementation of life cycle thinking ○ Future sustainable practitioner positioning	*"I will initiate more extensive research of various materials and design products that are suitable for C2C and CE."* *"What I will implement into my life is a vow: I will not even buy a k-cup coffee maker in my life."* *"I will keep looking at materials and their relations to the environment in my design for the future."* *"I'll definitely keep the skills I've learned from this course to apply them in my future projects."*

For the second question on likelihood of knowledge learned transcending the course into future design practice, most answers leaned positive with themes of perspective change and career opportunities emerging. In industrial design, the utility of prototyping is integral to communicating design ideas in 3D form, can benefit ideation and refinement at different points in the design process, and help students

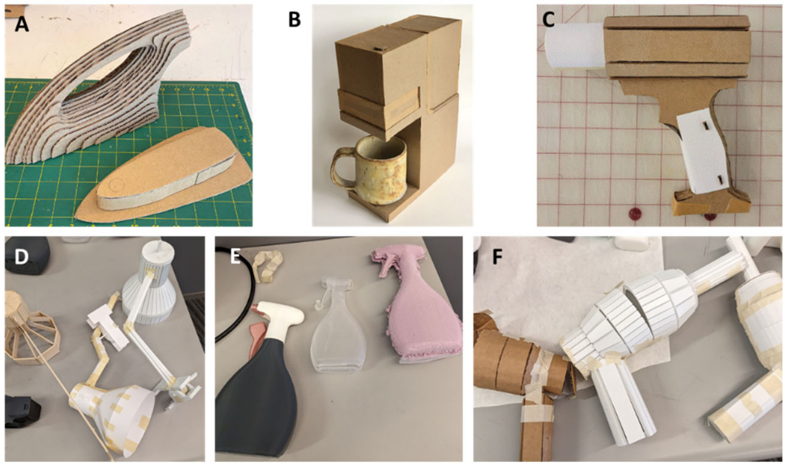

Figure 2. Examples of student prototypes. A-C were produced in Product Systems course, D-F shows replicate prototypes for the GMP comparison study

generate and evaluate ideas [3]. One student stated that they were able to think more about how the product would work and how a user would interact with it when they made their prototype by hand rather than digital to 3D print. This aligns with thinking that physical models allow designers to think more about real behaviours and help them identify and remove flawed design feature [14]. It could be argued that because most of the prototypes were made in recyclable materials, students were less fixated on the 'perfect' outcome, and more aligned with experimentation and troubleshooting. That most of the reflections written by students indicated a commitment in using the skills and tools learned in the course in further studies or in their careers was encouraging. This aligns with how industrial design education is transforming globally [4], [5]. The mixed sentiment responses typically included the need to better understand consumer behaviours, to think holistically about the product lifecycle, in addition to understanding the lifetimes of materials. Taken together, a readiness to think critically about the role of the designer in sustainability as an individual making prototypes, and as a future practitioner in industry was observed.

3.2 Global warming potential of materials

Global warming potential was calculated in a limited scope LCA for commonly used prototyping materials. The purpose was to compare impacts for replicate prototypes produced in different materials (*Figure* **2**D-F). Table 2 shows the datasets from which GWP was calculated for each prototype. For foam board data, a similar foam board from the Cultural Heritage database was used [15], and in the case of SLA resin whose composition is trade secret, an approximate formula was calculated using published data [16]. PLA global warming potential data was taken from a Ghomi et al., 2021 study [17].

Table 2. Information used to calculate material impact GWP

Material	LCA data source	Model	GWP kg CO2 eq/kg	GWP for model
Basswood	IDEMAT 2021	Lamp		0.07
Bristol Paper	Ecoinvent 3.9.1	Lamp	0.843	0.01
		Speaker		0.05
		Remote control		0.01
		Vacuum		0.01
Corrugated cardboard	Ecoinvent 3.9.1	Speaker	1.4	1.97
		Remote		0.08
		Vacuum		0.03
Foam board	Cultural heritage database	Lamp	1.5	0.16
		Speaker		1.50
		Vacuum		0.01
XPS	Ecoinvent 3.9.1	Camera	4.46	0.36
		Spray bottle		0.21
		Allergy packaging		0.28
PLA	Ghomi et al.,	Camera	3.5	0.89
		Spray bottle		0.56
		Allergy packaging		0.13

SLA resin	Ecoinvent 3.9.1 with calculated allocation	Camera	7.15	4.21
		Spray bottle		1.94
		Allergy packaging		0.30

There were a range of GWP values dependent on material used and the size of the prototype. For example, the Bluetooth speaker was significantly larger than any other product selected by the students to model and generally produced more wasted offcuts than other prototypes, had higher GWP than other board-based prototypes. For models of comparable size, *Figure **3***A shows that Bristol paper has the lowest impact for a looks-like prototype. For more rigidity so that the task lamp prototype can be held and manipulated, basswood would be a less impactful choice than foam core. This is similar to the vacuum cleaner prototype, with cardboard instead of basswood. For machined prototypes (*Figure **3***B), SLA resin had the biggest GWP, followed by 3DP PLA, then milled XPS for both the camera and spray bottle prototype. Regardless of material, process, or prototype geometry, opportunity to think critically about how to minimise waste in production was evident shown with the grey bars.

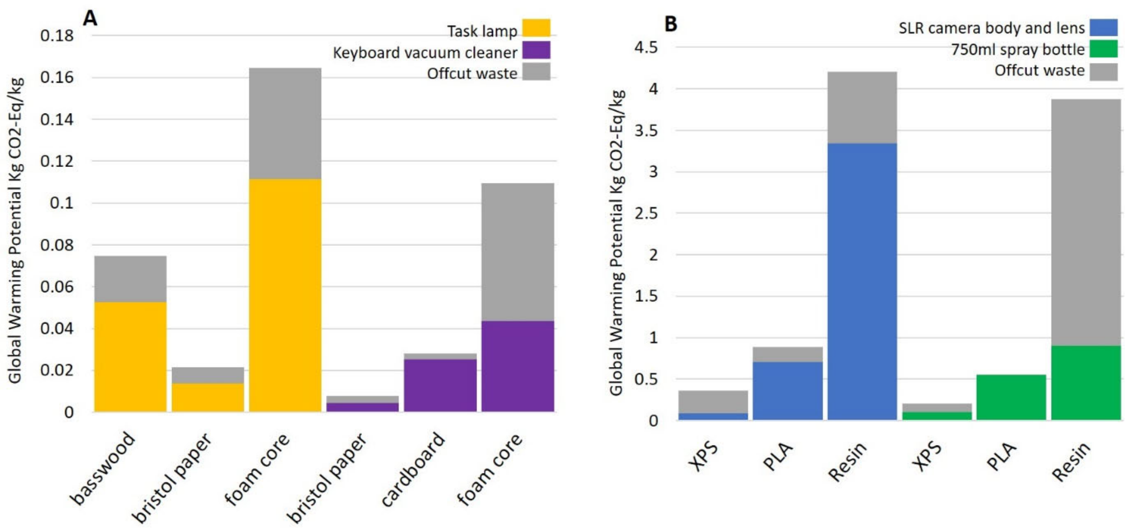

Figure 3. GWP comparisons for prototypes of 4 different products, each made of three different materials

There are limitations to the LCA study. Consumables, electricity costs to run the machine, and the transportation of supplies to the design studio were not factored. The GWP cost of the resin printing, for example, does not account for the washing or curing stages of SLA resin printing. Studies have shown that these additional stages, PPE required for safe handling, and electricity usage in all additive and subtractive manufacturing adds to the overall GWP impact [16], [18]. As seen is *Figure **3***B, there was a large amount of wasted materials, some of which could have been avoided with training in optimal 3DP and CNC settings [19]. In addition to the manufacturing stages, there are less obvious environmental cost of digital prototyping, such as computer usage for CAD models, the data centre use for AI-driven visualisation processes such as text-to-image applications like Stable Diffusion [20].

4 CONCLUSION AND FUTURE RESEARCH

This small-scale study adds to the growing literature on embedding sustainability literacy and actionable skills into the undergraduate design curriculum. These skills are needed to tackle climate change, challenge the take-make-waste process that proliferates the studio and beyond, and give students access to the necessary tools to critically assess when and if materials should be used in the product development process. From a pedagogical ethics perspective, how we teach future designers to prototype and explore ideas in the studio should align with the concepts we are teaching them to apply in industry. Research that extends beyond this pilot is already underway in the School of Engineering at Brown University. In collaboration with multiple project-based learning courses that combine the design and engineering processes, we are collecting data from looks-like through to works-like prototypes for LCA aggregations as well as understanding student sentiment to the process from reflection statements. Collaboratively, we are reinforcing waste-awareness and developing environmental impact limitation strategies whilst building a cross-course reuse and repurpose economy that spans academic semesters and disciplinary boundaries.

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