Exploring Processes That Foster Innovative and Sustainable Product Design

by
Sadie Boyle

A THESIS

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering
(Honors Associate)

Presented May 27, 2016
Commencement June 2016

AN ABSTRACT OF THE THESIS OF

Sadie Boyle for the degree of Honors Baccalaureate of Science in Mechanical Engineering presented on May 27, 2016. Title: Exploring Processes that Foster Innovative and Sustainable Product Design .

Abstract approved:

Bryony DuPont

As global population and affluence continues to rise, demand for and disposal of consumer products is increasing. Currently, there are established process that guide designers to develop innovative products, but these products still have a large impact on the environment. There is beginning to be an emphasis on product sustainability, and currently there are tools to aid designers in making sustainable products; however, most of these tools require designers to have fully-formulated designs, having already made key design decisions. Currently, there is no early-phase design process that leads to both innovative and sustainable products. Through a graduate level sustainable product design course at Oregon State University there is an opportunity to advance how mechanical engineering students learn about sustainability in mechanical design. This research seeks to redevelop a sustainable design process and embed it in this graduate-level course. Through the redevelopment of this course, student learning focuses on sustainability through the development of six different concept generation lenses: materials, manufacturing, energy use, biomimicry, upcycling/remanufacturing, and systems-level sustainability. The sustainable design method employed in the 2016 course, while still ongoing, is considered to be an improvement on its earlier version, allowing students to create both sustainable and innovative products.

Key Words: Sustainable Design, Innovation, Design method, Design process

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Sadie Boyle, Author

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Introduction

In 2013, Americans produced 254 million tons of waste, and of that waste only 87 million tons were recycled [1]. The rate of recycling and incentives to reclaim and remanufacture consumer goods is on the rise, but even with this increase, everyday consumer products (such as coffee makers and clothing) are bought, used, and discarded of at the end of their useful life. All of the materials in these consumer products require natural resources. Plastics require fossil fuel; metals require ore; and most materials require large amounts of water to produce. There is a finite amount of all three of these resources.

Not only are the resources required to make consumer products limited, but the processes required to create, use, and dispose of consumer products produce a significant amount of carbon dioxide (CO_2). According to the Environmental Protection Agency (EPA), CO_2 is the largest human contributor to greenhouse gas emissions [2], which is the leading cause of climate change [3]–[6]. The average American household produces 48.5 tons of CO_2 per year from travel, household electricity consumption, food, and consumer products [7].

Consumer and business interest in sustainable design is increasing. In a survey conducted on consumer interest 55% of consumers said they were willing to pay more for products produced companies that have an emphasis on reducing their environmental impact [8]. Not only do consumers have an interest in sustainability but in a survey conducted on practicing engineers 40% responded that they were 'extremely interested' in sustainable causes [9].

With the combination of the continuing upward trend of population growth and increasing affluence globally, the demand for consumer products will surge [10]–[12]. With decreasing resources and increasing demand for products on a global scale, we must find a way to create consumer products that have a significantly reduced environmental impact. The work that constitutes this thesis focuses on how to teach sustainability in product design as part of an engineering curriculum, through the development of a sustainable product design method taught in a graduate-level mechanical engineering course. As such, the thesis statement this research seeks to prove is:

> There is an opportunity to embed sustainability in engineering education by advancing how graduate level mechanical engineering students at Oregon State University learn about sustainability in mechanical design, through adapting and combining material in innovative product design and design for the environment during concept generation.

For the purpose of this research sustainability is defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [10]. Sustainable products are defined as "products that provide environmental, societal, and economic benefits while protecting social health and welfare, and maintaining the environment over their full life cycle from raw materials, extraction, and use, to eventual disposal and reuse" [13].

The following introductory material is divided into three sections: (1) Design Processes, (2) Methods for Sustainable Design, and (3) Current State of Sustainable Product Design at Oregon State.

(1) Design Processes

The product design process traditionally used and taught at Oregon State University is the Ullman method for mechanical product design [14], which is outlined in Figure 1.

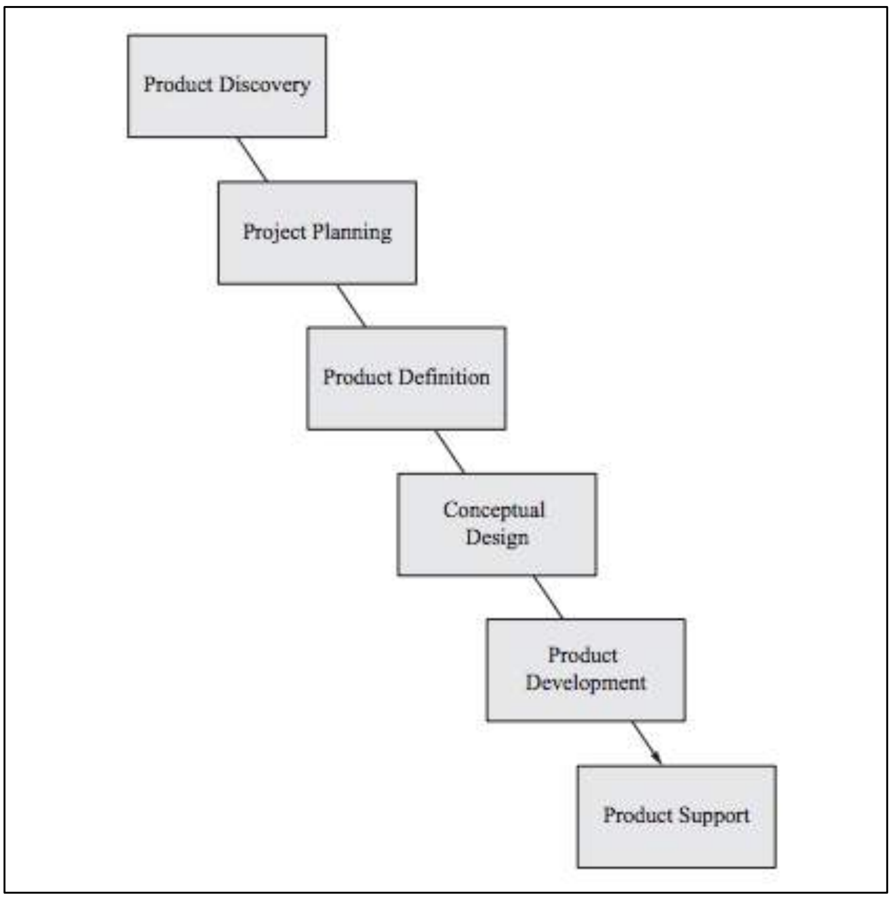

Figure 1: Steps of Ullman Design Process [14]

The Ullman method is based on customer-centered design. The process starts with product discovery and ends with product support. A list of customer requirements is created, and from them, a measureable set of engineering specifications is generated. This process can be adapted for most products but it is not specific to any type of design method, such as design for manufacturing or design for sustainability.

Another product design method is in Cagan and Vogel's book, *Creating Breakthrough Products* [15]. This method is focused on creating innovative products that either create new markets or redefine current markets; products that do this are considered to be high value. High-value products are both high technology and high style [15], which is shown on the positioning map of style versus technology in Figure 2.

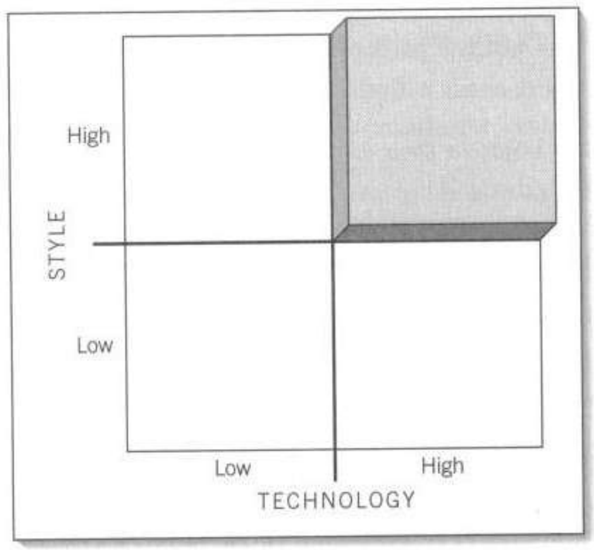

Figure 2: Positioning Map of style versus technology. Cagan and Vogel believe that great products are value-driven and driven toward the upper right corner of the map [15]

(2) Methods for Sustainable Design

There are tools to aid in sustainable product design. They range in their complexity, and at what phase in the design process they can be used. Common sustainable design tools are shown on the plot in Figure 3. The graph maps when in the design process each sustainable design tool can be used, and how in-depth the method is.

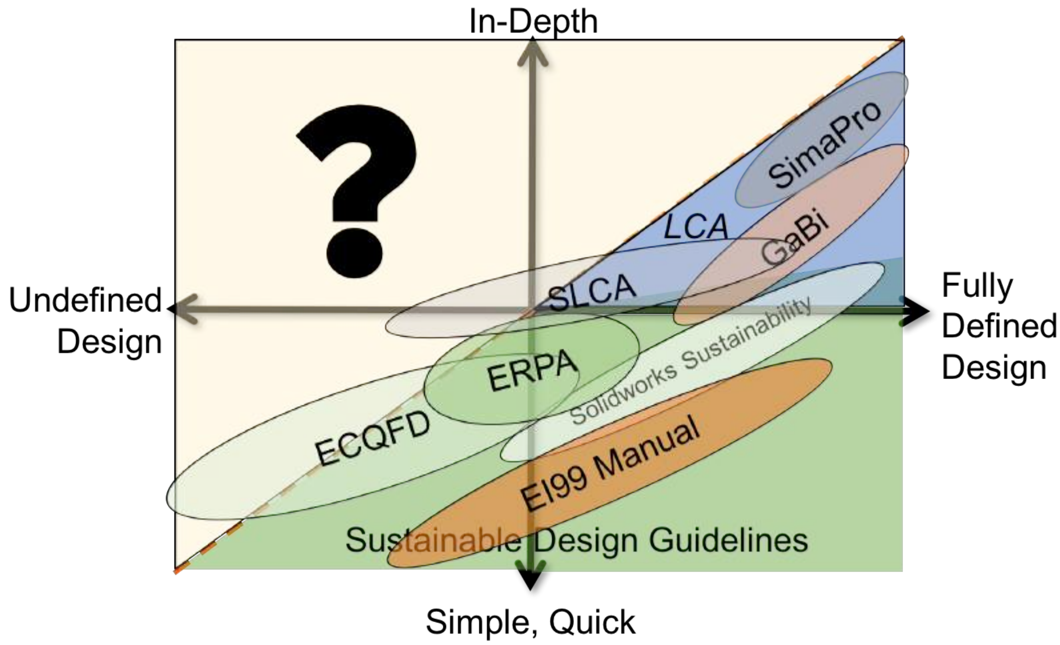

Figure 3: Graph of sustainable design tool complexity verses how defined the design must be in order to use the tool [16]

All of these design tools have their benefits and their setbacks. Environmentally-Conscious Quality Function Deployment (ECQFD) and the sustainable design guidelines help to implement sustainable design considerations early in the design process, but neither lead to a quantitative analysis of the environmental impact of a product (lower left quadrant). Environmentally Responsible Product Assessment (ERPA) and the Simplified LCA (SLCA) are quantitative methods that can be used earlier in the design process and provide a more in depth analysis (origin of graph) but still require many design decisions to be made prior to use. ERPA uses matrices to look at the impact of individual phases of a product [17]. SLCA is a less-expensive LCA method that requires less input information [18], [19]. ReCiPe (in the software GaBi) and Solidworks Sustainability are both commonly used methods for product lifecycle analyses. They both require all design decisions to be made, and these methods provide quantitative metrics for a product (right side of graph). SimaPro is commercial software that includes various life-cycle assessment methods (including CML, ReCiPe, and BEES) that requires a fully developed design (upper right quadrant).

The most common means of determining the impacts of a product is Life Cycle Analysis (LCA). LCA is used to access the environmental impacts of a product from cradle to grave [20]. It identifies the opportunities to improve on the environmental impact of a product, helps industry to make decisions, and contributes to marketing. An LCA consists of four phases; goal and scope definition, inventory analysis, impact assessment, and interpretation. These methods are widely used and provide information on the environmental impact of a product, but LCA is performed retrospectively, is not a design method, can be time consuming, and is not generally used to address the social or economic impacts of a product (upper right quadrant) [20], [21].

The EI-99 Manual [21] was developed specifically for product design. The tool turns LCA results into comparable values by using previously-collected data for the most common materials and process. These numbers represent the total environmental load of a product or process throughout its life cycle. The Eco-indicator focuses on environmental damage by focusing on human health, ecosystem quality, and resources. There are five steps to the eco-indicator analysis method; establishing the purpose of the analysis, defining the life cycle, quantify materials and processes, fill out tables, and interpret the results. Unlike LCA, the Eco-indicator values were not intended for marketing or to be used to set governmental standards, but instead it is meant to be a tool that designers can use to look for more environmentally friendly alternatives.

From the graph in Figure 3, it is very clear that there is a large gap in the upper left quadrant. There are no formalized design methods that allow designers to quantitatively understand the environmental impact of potential design decisions early in the design process, and there are no existing methods for designers that simultaneously encourage the creation of both innovative and sustainable products.

(3) Sustainable Product Design at Oregon State MIME

At Oregon State University (OSU) [22], first-year mechanical engineering students have the option to take the "Going Green" section of the Introduction to Mechanical, Industrial, and Manufacturing Engineering course. Undergraduate students are also exposed to sustainable design principles during their junior year Introduction to Mechanical Design course, and during their senior year students have the option to do sustainability-focused capstone design projects. Through these classes, students can learn sustainable design principals, and while this content can help students to make sustainable design choices, they do not provide a comprehensive process to create innovative and sustainable products. For College of Engineering graduate students at OSU, there is a class specifically focused on sustainable product design. In this thesis, the redevelopment of this class is discussed, the goal of which is to create a process that allows to students to create innovative and sustainable products.

The class went through its first iteration in 2015. The 2015 course primarily followed the integrated product design method (from *Creating Breakthrough Products*) with sustainability-related content inserted throughout. This was beneficial because the course progression flowed well due to using the established method; however, students didn't necessarily feel they were learning about sustainability but instead learning about product design. For 2016, changes were made to the course to make it more oriented on sustainability and to include more related content than the previous year. Additionally, the course content was influenced by current lecturers at The University of California, Berkeley (*Human-Centered Sustainable Product Design*), the Masters of Sustainable Design at the Minnesota College of Art and Design (*Green Product Design)* and Stanford University (*Green Product Design*).

To do this, the course was restructured to focus on concept generation. While in the previous class concept generation was accelerated, the 2016 class centers around three weeks of concept generation through six different lenses. The six lenses are materials, manufacturing, energy use, biomimicry, upcycling/remanufacturing, and systems-level Sustainability. After each lens the students generated new concepts, allowing them to focus on particular aspects of sustainable design, with the overarching goal of developing concepts that are sustainable on a systems level. If successful, this method developed for this class will enable the consideration of product environmental impact in the preliminary design phase—prior to and during concept generation—providing a quantitative analysis of the effects of design decisions, and potentially leading to a new paradigm of environmental impact reduction in the design of new consumer products.

Methodology

The goal of this thesis project is to develop a second iteration of a product design method that will incorporate sustainable design thinking throughout an open-ended product design process. This method will be applied to the second iteration of Sustainable Product Design (SPD), a graduate level course taught at Oregon State University (OSU).

The first iteration was in spring of 2015. The course used integrated product design (IPD), an overarching design method, and inserted sustainable design tools into the process. The basic structure of the process is show in Figure 4.

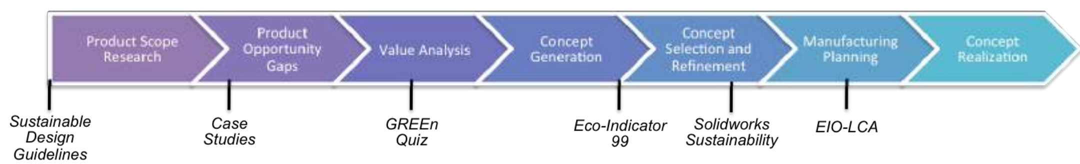

Figure 4: Integrated product development process with incorporated sustainable design principles

In the course, students were divided amongst three teams. The goal of the course is to create patent-ready systems-level sustainable products and for students to reach the following educational objectives based on Bloom's Taxonomy [23]

1. Identify factors that lead to sustainable products
2. Illustrate design intent through technical reports and presentations
3. Operate in a professional multidisciplinary design team
4. Employ the integrated product design method in the design of a sustainable product
5. Create a product that is patent ready and sustainable on a systems level
6. Asses the environmental impact of a product using commercially available software

To achieve this goal, students are taught an integrated design process that incorporates sustainable design tools, such as LCA and the GREEn Quiz [22]. The 2015 course schedule is shown in Figure 5.

Week 1
SET Factors

Week 2
Innovation Spheres
Products Opportunity Gaps
Market Identification
List Reduction

Week 3
List Reduction
Pugh Matrices
Stakeholder Identification
Scenario Development

Week 5
User-Based Research and Field Research
Value Opportunity Analysis (VOA)
Field Research

Week 6
Value-Based Product Specs
GREEn Quiz
Product Constraints

Week 7
Product Conceptualization from VOA

Week 8
Information Synthesis
Market Analysis
Pugh Chart
Develop Selection Criteria

Week 9
Product Plan
Concept Refinement
Concept Selection

Week 10
Life Cycle Assessment (LCA)

Figure 5: 2015 Sustainable Product Design course schedule. Highlighted in Orange is the integrated product design method and in green is the sustainability tools inserted into the course

In 2015 each student was instructed to generate ten concepts individually with no guidance on brainstorming methods.

For the 2016 Sustainable Product Design course, we sought to change this process. The goal was to streamline the design method and have the focus even more honed in on sustainability. When researching improvements for the 2016 SPD course the concept generation process seemed the most obvious area for improvement. It has been found that there is a correlation between the time spent on concept generation, the amount of concepts generated, and the quality of the outputted design [24]. Significant changes were made to the 2016 course based on this research. The 2016 schedule can be seen in Figure 6.

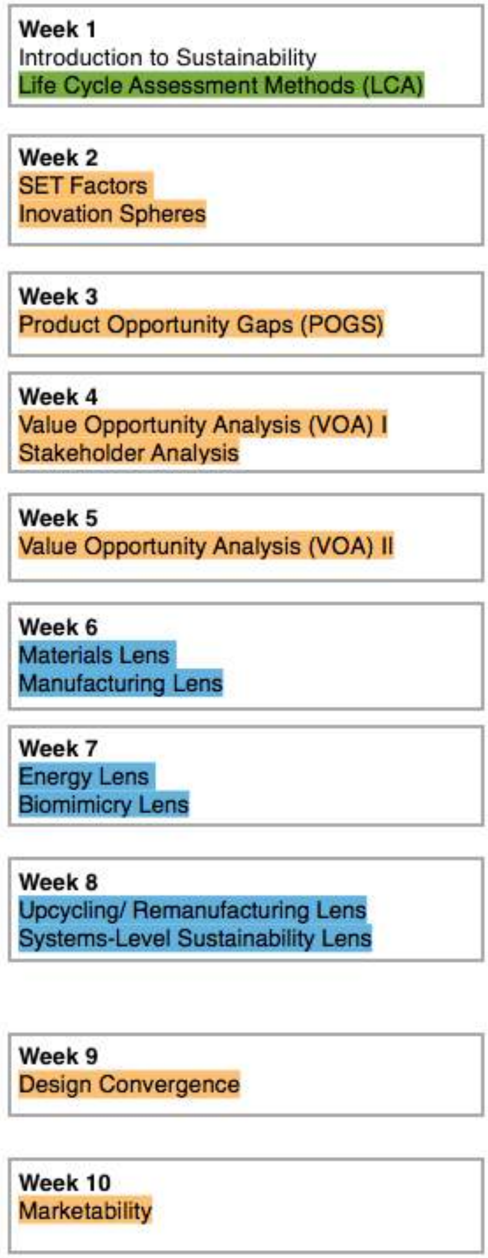

Figure 6: 2016 Sustainable Product Design course schedule. Highlighted in orange is the integrated product design method, in green are the sustainable design tools used in the course, and in blue is the concept generation process

The process expands concept generation from one slide of one lecture in 2015 to three weeks of the course and introduces sustainability on the first day of the course in 2016. The method employed in the 2015 course is compared to the method employed in the 2016 course in Figure 7.

Week 1	SET Factors	Introduction to Sustainability Life Cycle Assessment Methods (LCA)
Week 2	Innovation Spheres Products Opportunity Gaps Market Identification List Reduction	SET Factors Inovation Spheres
Week 3	List Reduction Pugh Matrices Stakeholder Identification Scenario Development	Product Opportunity Gaps (POGS)
Week 4		Value Opportunity Analysis (VOA) I Stakeholder Analysis
Week 5	User-Based Research and Field Research Value Opportunity Analysis (VOA) Field Research	Value Opportunity Analysis (VOA) II
Week 6	Value-Based Product Specs GREEn Quiz Product Constraints	Materials Lens Manufacturing Lens
Week 7	Product Conceptualization from VOA	Energy Lens Biomimicry Lens
Week 8	Information Synthesis Market Analysis Pugh Chart Develop Selection Criteria	Upcycling/ Remanufacturing Lens Systems-Level Sustainability Lens
Week 9	Product Plan Concept Refinement Concept Selection	Design Convergence
Week 10	Life Cycle Assessment (LCA)	Marketability

Figure 7: 2015 Sustainable Product Design course schedule (right). 2016 Sustainable Product Design course schedule (left). Highlighted in orange is the integrated product design method, in green are the sustainable design tools used in the course, and in blue is concept generation

For the 2016 course both sustainable design and LCA are introduced in the first week, the IPD method is condensed into four weeks, three weeks are spent on guided concept generation, and the last two weeks of the course finish the IPD method.

Faludi [25] suggests that methods focused on idea generation could lead to more sustainable products. With this in mind, sustainable products were surveyed and it was found that sustainable products are

- designed with materials that have low environmental impact
- designed with manufacturing processes that have low environmental impact
- designed to reduce their energy use
- designed to be remanufactured
- designed to be upcycled or are made with upcycled materials
- designed for efficiency using biomimetic principles
- designed knowing how they will impact the system in which they function in

Using these findings the sustainable design process was changed to focus on concept generation through a series of six lenses that are focused on these principles. Figure 8 shows the 2016 iteration of the sustainable product design method.

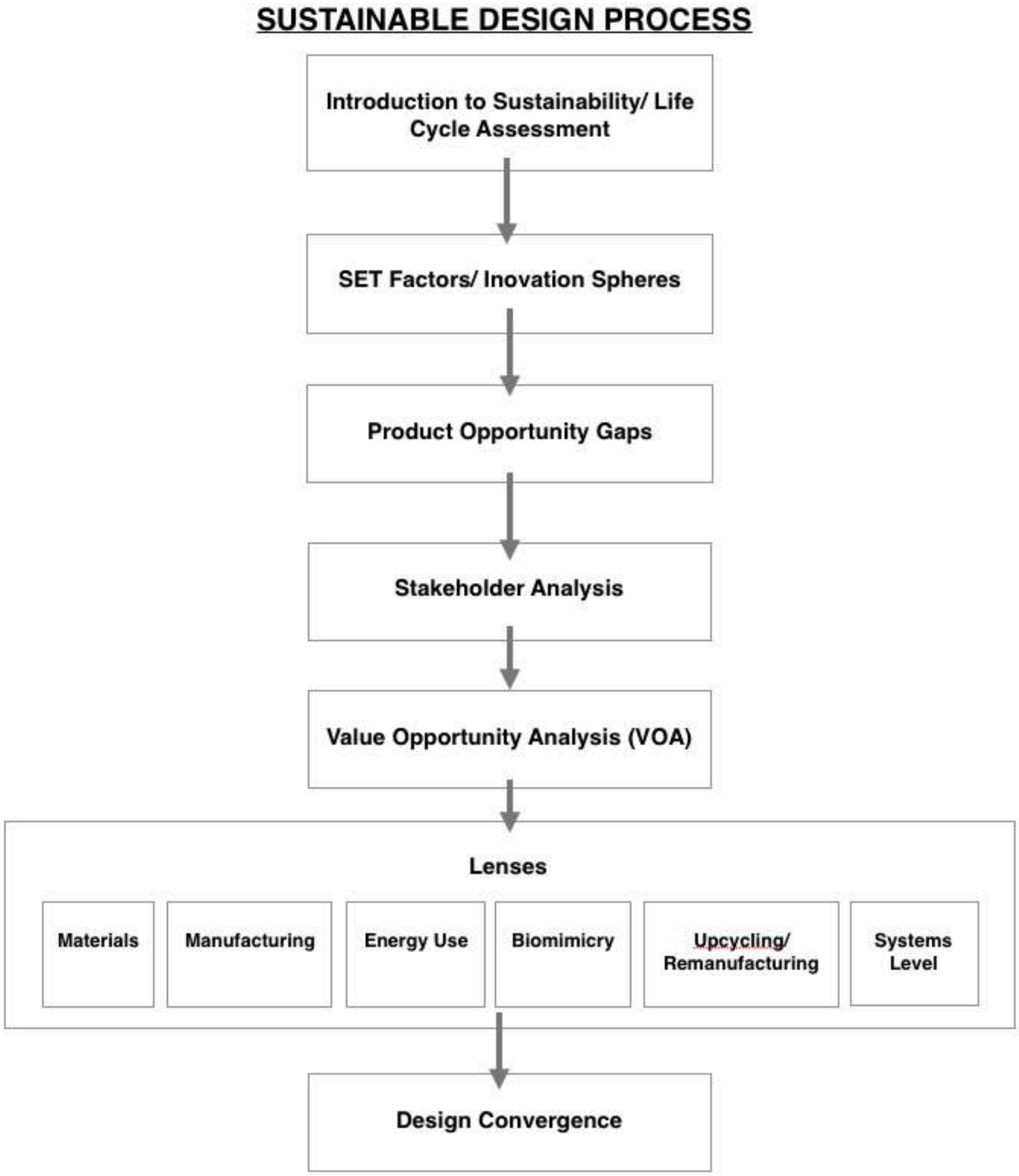

Figure 8: 2016 Sustainable Product Design Process

The method is centered around the six lenses: 1) Materials, 2) Manufacturing, 3) Energy Use, 4) Biomimicry, 5) Upcycling/Remanufacturing, and 6) Systems Level. The goal is for students to be presented with different foci and then use a different brainstorming method after each lens to generate concepts. These lenses will expose students to information that affects the sustainability of products they are designing. This will encourage students to continue to think creatively and to not get fixated in one design space. Because they are exposed to varied information, students are more likely to make design choices that lead to more sustainable products. The following sections will describe each design lens in detail.

Materials Lens

The goal of this lens is for students to understand that material choice has a large impact on a product's sustainability. The students are asked to meet function first (determine the functions necessary for their product concept to operate) and then figure out how to make their product sustainable through informed material choices. The information presented in this lens focuses on the materials engineers most commonly use, including plastics, bioplastics, steel, aluminum, copper, glass, wood, leather, wool, plant fibers, and composites. All materials lens lecture material can be found in Appendix A The students use the information in the lecture and the table in Appendix B to generate three different fully formed concepts through traditional individual brainstorming.

Manufacturing Lens

The goal of the manufacturing lens was for students to understand how available manufacturing processes affect design choices, and in turn affect the environmental impact of a product. The focus of this lens was on forming, the most common of the four manufacturing processes engineers use: forming, cutting, joining, and finishing. The students used the information provided in lecture, which can be found in Appendix C along with the tables in Appendix D to generate concepts using the 5-3-5 method.

The 5-3-5 method allowed all five (the first "5" of "5-3-5") team members to participate equally. Each team member had a clean piece of paper and divided it into three columns (the "3" of "5-3-5"). Each team member then started one idea in the first column and worked on it for five minutes (the last "5" of "5-3-5"). Once time was up, the piece of paper was passed to the next team member and they added to the previous team member's idea, and this process was repeated such that three team members were all contributing to the development of a single concept.

Energy Use Lens

The goal of this lens is to have students understand that the amount of energy consumed throughout the life of a product has a very large effect on the product's sustainability. According to the U.S. Energy Information Administration [27] residential energy use accounts for about 10% of total U.S. energy consumption, including heating and cooling, travel, and household appliance use. Through this lens we wanted to highlight that if a product consumes energy during its use phase, this is likely to be the largest impact on the embedded energy of the product.

Students are exposed to different examples of products highlighted in Widermann's Product Design for the Sustainable Era [26] that are focused on reducing their energy impact. The product were the Homegrown Project: Remade Nokia First Phone/Nokia Zero Waste Charger, Recompute, Inlet-Outlet, Leaf, RITI Printer, and GEnX Engine and are shown in Figure 9. The lecture material for the energy use lens can be found in Appendix E.

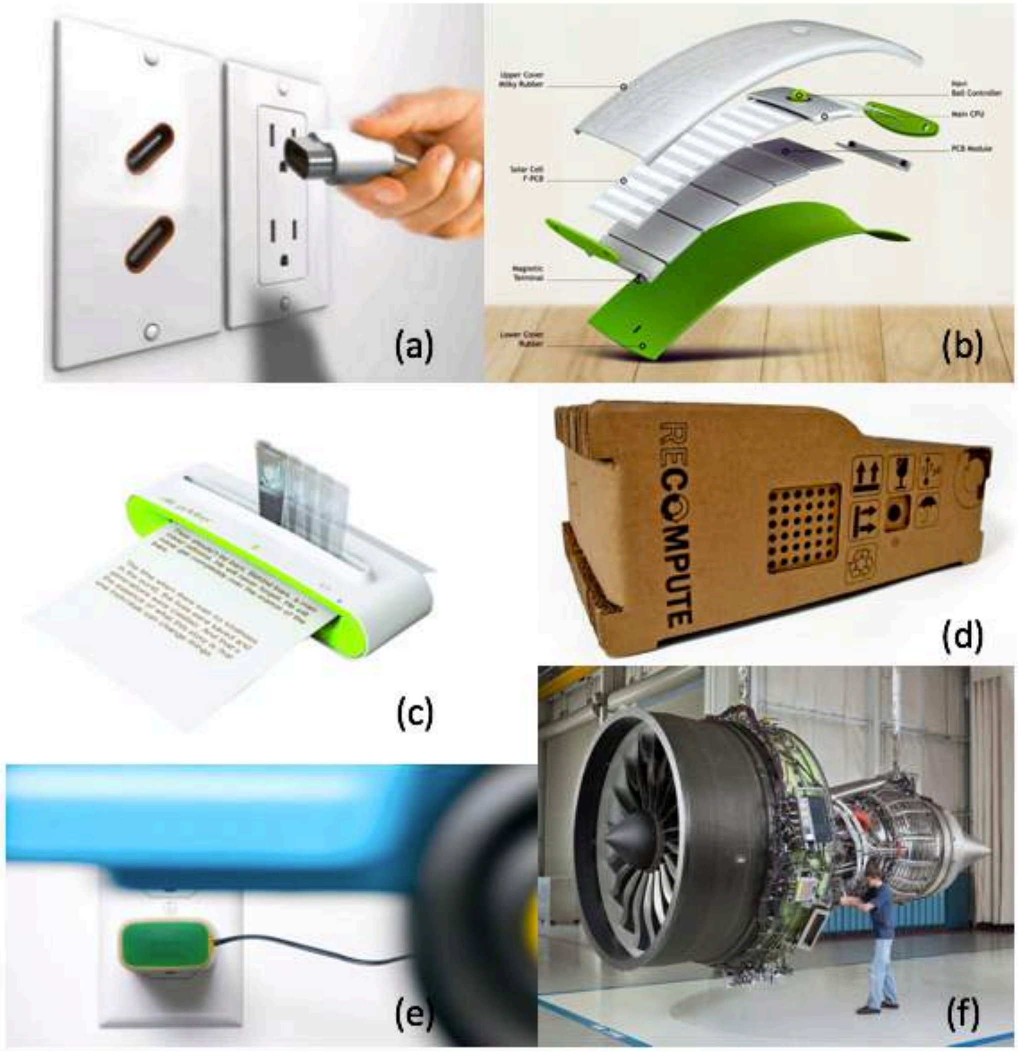

Figure 9: Products designed for reduced energy impact: (a) Inlet-Outlet (b) Leaf (c) RITI Printer (d) Recompute (e) Homegrown Project: Remade Nokia First Phone/Nokia Zero Waste Charger (f) GEnX Engine [26]

The students then work through concept generation using the Brainball method. For this method each team was given a ball. The person with the ball would come up with a solution for the given problem and then throw the ball to one of their teammates who would come up with another solution to the given problem. This process continued for a given amount of time. The goal of the Brainball method is to think of new solutions quickly, without filtering, and to build on solutions presented by teammates.

Biomimicry Lens

Biomimicry is being inspired by nature. It is using the design principles found in nature and applying them to the design at hand [28]. The purpose of this lens is for students to come to the conclusion that although "biomimetic" does not inherently mean "sustainable", by mimicking how nature solves its problems we can be lead to more sustainable design choices. Students are presented with examples of biomimetic principles that have been used to create products that humans use. Such product ideas come from capillary action in plants, the principles of how gecko feet can stick to anything as an inspiration for adhesives, the hook and loop attaching system found on the burdock plant as an inspiration for Velcro, birds wing shape for how we make plane wings, baleen as an inspiration for water filtration systems, and coral CO_2 absorption. The lecture material for the biomimicry lens can be seen in Appendix F. After the lecture students generate three concepts each using the website AskNature [29] to explore natural solutions for product functions.

Upcycling/Remanufacturing Lens

Upcycling is the process of converting a discarded product into something new and useable [30]. Remanufacturing is the process of returning a used product to its original state [31].

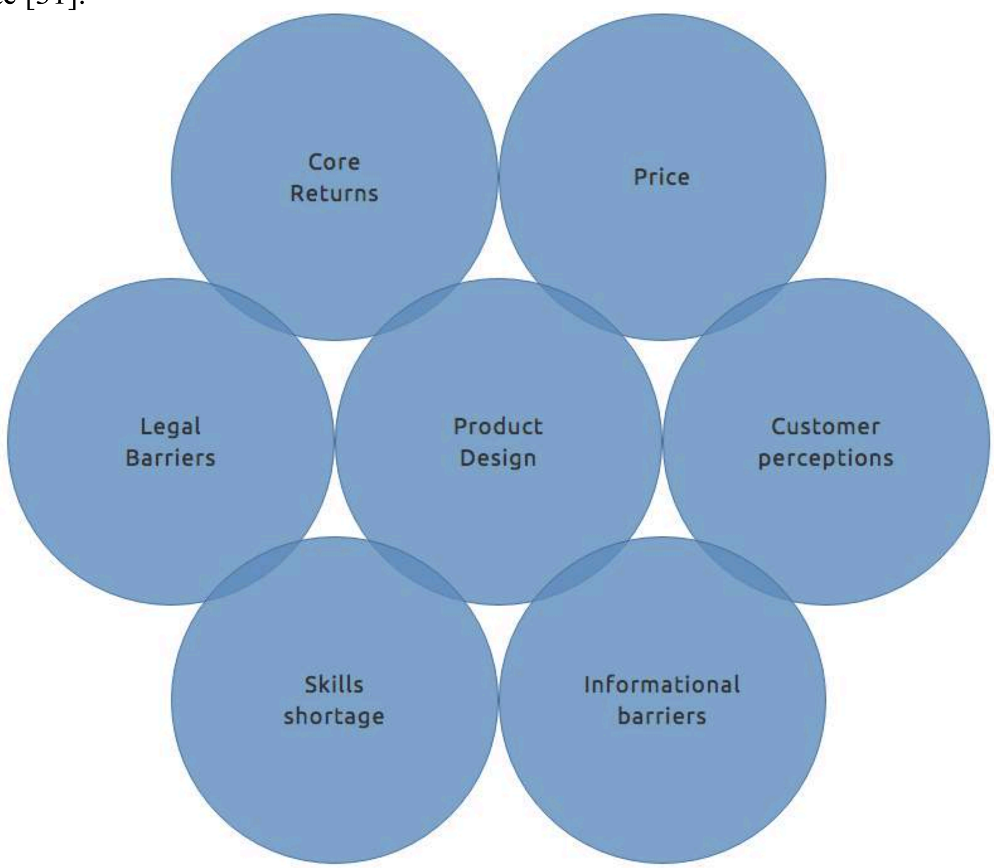

Figure 10: Challenges associated with remanufacturing [31]

As show in Figure 10, there are many challenges associated with remanufacturing, and the field that has purview over accommodating these challenges is product design. The goal of this lens is for students to understand that in order for a product to be remanufactured it must be designed to be remanufactured. This includes designing products for disassembly with components that can be easily replaced and tested. The lecture material for the upcycling/ remanufacturing lens can be seen in Appendix G. After the lecture, students use mind maps and the UpcycleThat [32] website to generate unique concepts.

Systems Level

For a product to be truly sustainable it must be sustainable at a systems level. For example, instead of designing a more sustainable car (starting with the design and function of a traditional car), the designer creates a way to travel that eliminates the need for personal vehicles. Systems-level sustainability is challenging to teach because it is abstract, but the goal of this lens is to have students combine the knowledge they have gained over the course and think about sustainability on a larger scale. The lecture material can be seen in Appendix H. After the lecture, students use the gallery method to generate concepts. In this method, each team member writes an idea to solve a given problem statement on a piece of paper. Those ideas are then pinned around the room. The students walk around the room and look at the ideas and then return to their own work to build off their own or others ideas.

After students generate concepts through the information presented in each lens, they converge on one design, and create a marketing plan, CAD models, a presentation, and a report for the chosen design. At the time of writing, students have not yet completed design convergence for the 2016 course.

Results and Discussion

The following sections discuss comparisons between the 2015 course and the 2016 course, and the results of the students work from both the 2015 course and the 2016 course.

(1) *2015 versus 2016 Course Comparisons*

The 2015 SPD course used an integrated product design (IPD) method with sustainability tools inserted throughout the process. The majority of the effort in the course was focused on the front end of the design process and systems-level sustainability was not discussed at all during the course.

The 2016 SPD course compressed the IPD method from the 2015 course into the four weeks of the class (weeks 2-5) and focused three weeks on concept generation. Concept generation was conducted in a studio format, by introducing the lenses and giving students prescribed brainstorming methods that were then worked through in class. Students were given a lecture in basic drawing techniques and concept generation, and were required to develop a digital design notebook to compile their team's 55 designs.

The course overall was more guided than the previous year. Students were told what to focus on during concept generation and how to brainstorm ideas, whereas during the 2015 course students were not given specific direction during concept generation.

(2) Student Product Results from the 2015 Course

One team's solution from the 2015 course for the design scope "Getting to Campus" was a regenerative braking system for a bicycle [33]. The original concept can be seen in Figure 11. This design was chosen during the concept selection section of the course. Other designs generated by this team can be seen in Appendix I.

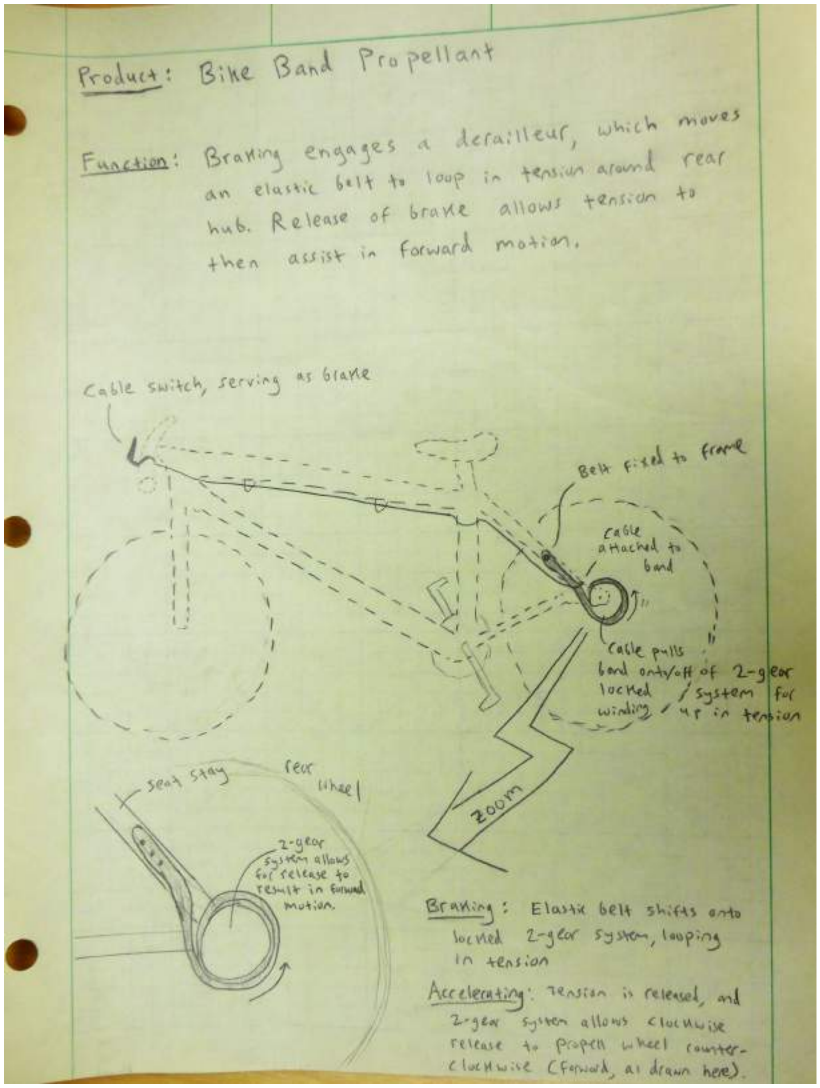

Figure 11: Original concept for the bicycle regenerative braking system [33]

After the design was selected and refined, the team conducted an LCA on their product. They used the Eco-indicator 99 and Solidworks Sustainability to conduct the analysis. The results from the Eco-indicator assessment can be seen in Table 1. The team's proposed spring-based product can harvest around 40% of the braking energy while biking [34].

Table 1: Eco-Indicator for Spring Based Regenerative Breaking [34]

Production			
Material	Amount	Indicator (millipoint)	Value
Steel low alloy	4.6 kg	110	506
Machining	0.5	800	400
Production Total	**906**		
Use			
Material	Amount	Indicator (millipoint)	Value
			0
			0
Use Total	**0**		
Disposal			
Material	Amount	Indicator (millipoint)	Value
Recycle Steel	4.6 kg	-70	-322
			0
Disposal Total	**-322**		
Total	**584**		

Use of the LCA method Solidworks Sustainability requires the creation of a Solidworks CAD model. From that model, the program takes the geometry information and determines the environmental impact of the products from four categories: air pollution, carbon emission, water pollution, and energy use. The team chose to view the impact difference from using a polypropylene spring housing verses a steel spring housing. The results from using polypropylene can be seen in Figure 12 and the results from using steel housing can be seen in Figure 13.

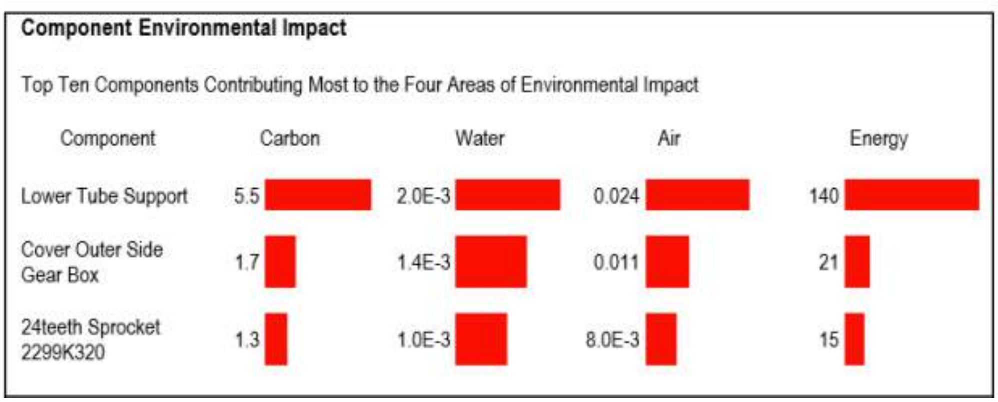

Figure 12: Solidworks Sustainability Results for Polypropylene Spring Housing [34]

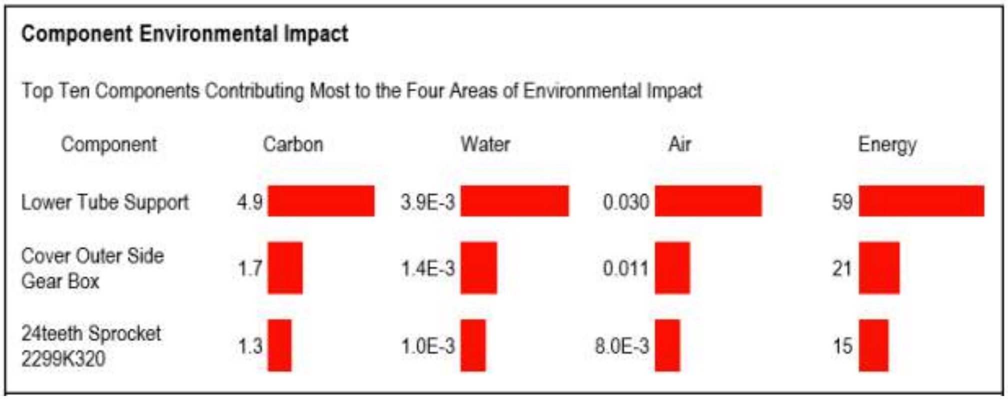

Figure 13: Solidworks Sustainability Results for an All Steel Design [33]

From these results, it became clear that the largest impact was from the steel spring. The team chose to use an all steel part because it was easier for the user to recycle and easier to manufacture the part if it was made from just one material [34].

(3) Student Product Results from the 2016 Course

Each student individually generated concepts based on five of the six proposed lenses. The upcycling/remanufacturing lens covered briefly during the systems level lens lecture but did not not have a dedicated lecture and no concepts were generated based on that lens. A sample of "The Best Part of Waking Up" team's concepts can be seen in Figure 14-18 [35]. More of the concepts developed by this team can be seen in Appendix J.

Figure 14 shows one of the team's concepts for the materials lens. The concept is a coffee filter made out of sustainable plant material.

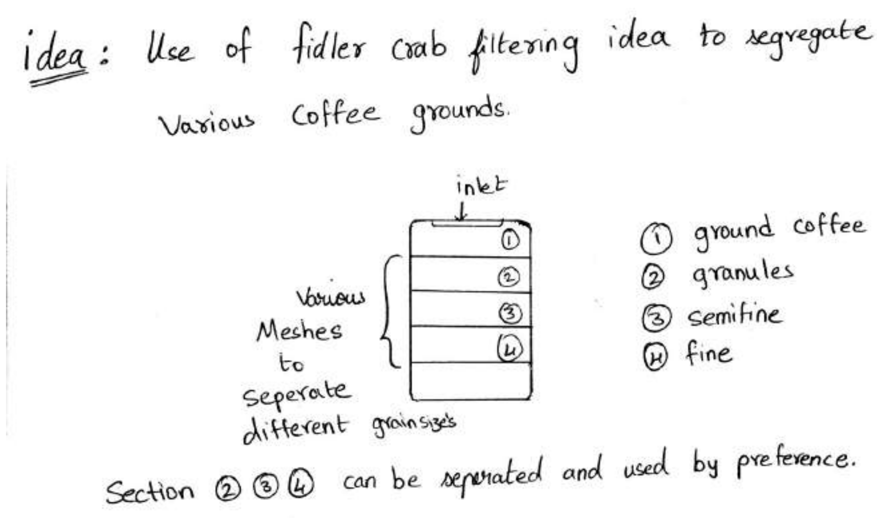

Figure 14: (Materials lens concept) Coffee filter made of plant material [35]

Figure 15 depicts a concept generated during the manufacturing lens. When doing research, it was found that toothbrushes are disposed of when their bristles wear out. The bristles are the easiest and least energy intensive part of the toothbrush to make. The concept is a tooth brush where the handle is made out of a durable material such as stainless steel and the bristles are a separate piece that can be bought and replaced separately form the rest of the toothbrush.

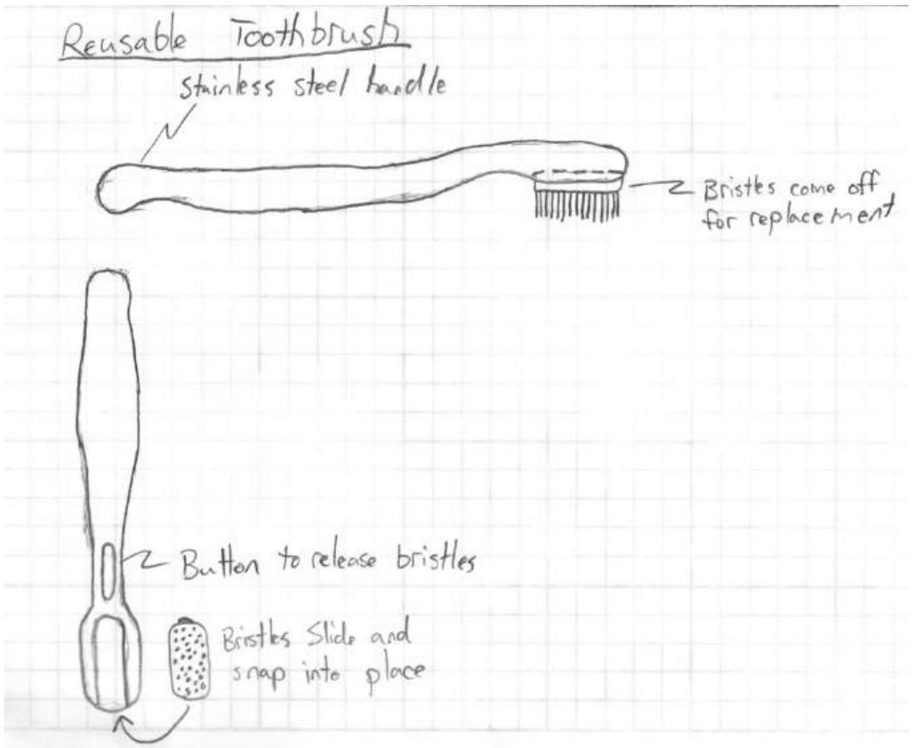

Figure 15: (Manufacturing lens concept) Reusable toothbrush with replaceable head [35]

Figure 16 shows a concept generated during the energy use lens. This bathroom sink concept uses an inline heater to reduce the need for hot and cold piping (huge energy loss) between the bathroom and the hot water heater and feeds grey water form the sink into the toilet.

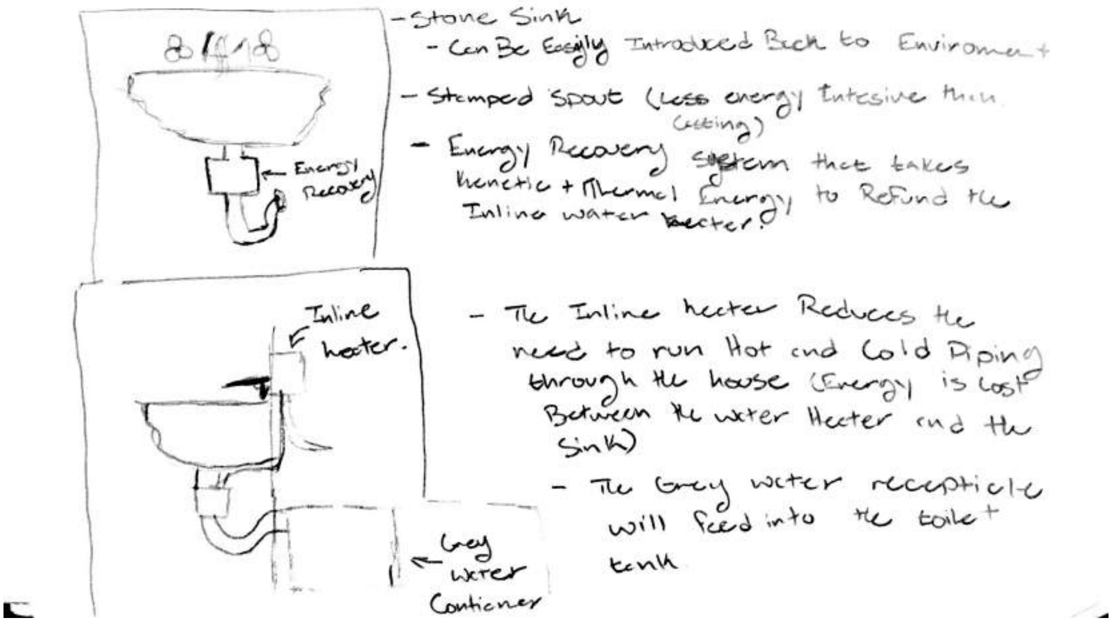

Figure 16: (Energy use lens) stone sink with stamped spout. The sinks provides hot water by using an inline heater [35]

Figure 17 shows a concept that was generated during the biomimicry lens. The concept is a comb modeled after the Darling Beetle. The beetle collects water from fog on its skin and it drains into its mouth for the beetle to drink. The comb uses the same principle; it moves the water away from the user's hair in turn drying it.

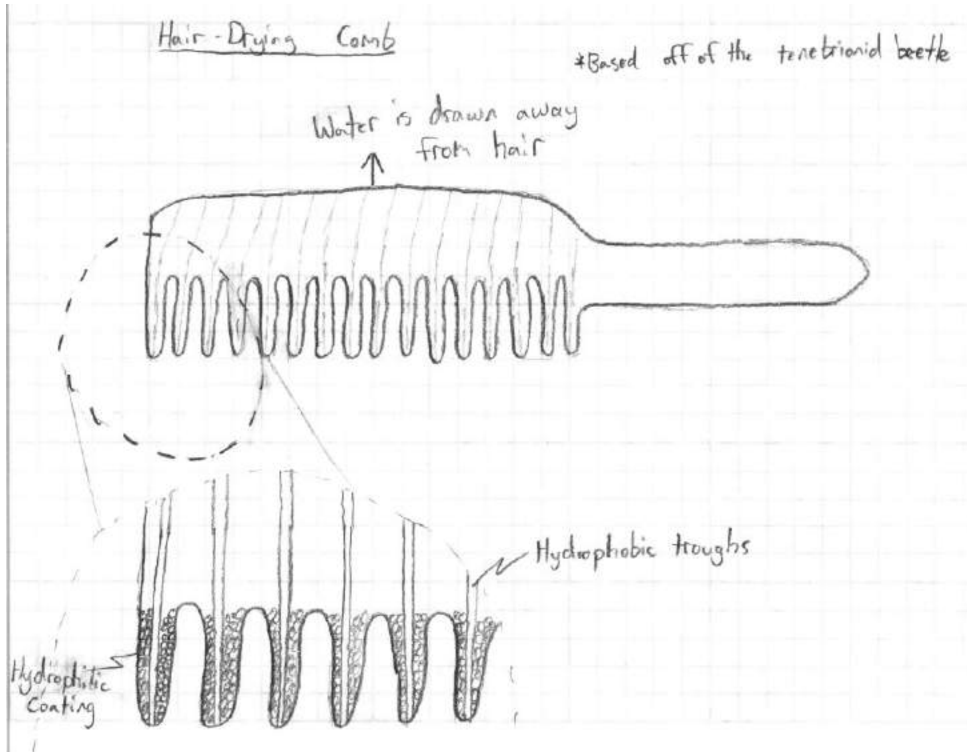

Figure 17: (Biomimicry lens concept) comb that dries hair by drawing water away from the hair. The water removal mechanism is based on the Darkling Beetle [35]

Figure 18 show a concept generated through the systems level lens. This concept addresses the time it takes for people to get dressed in the morning and gives the solution that everyone should wear uniforms. This would reduce the time needed to get ready in the morning, the time and energy spent on shopping, and make it easier to manufacture and repair clothing.

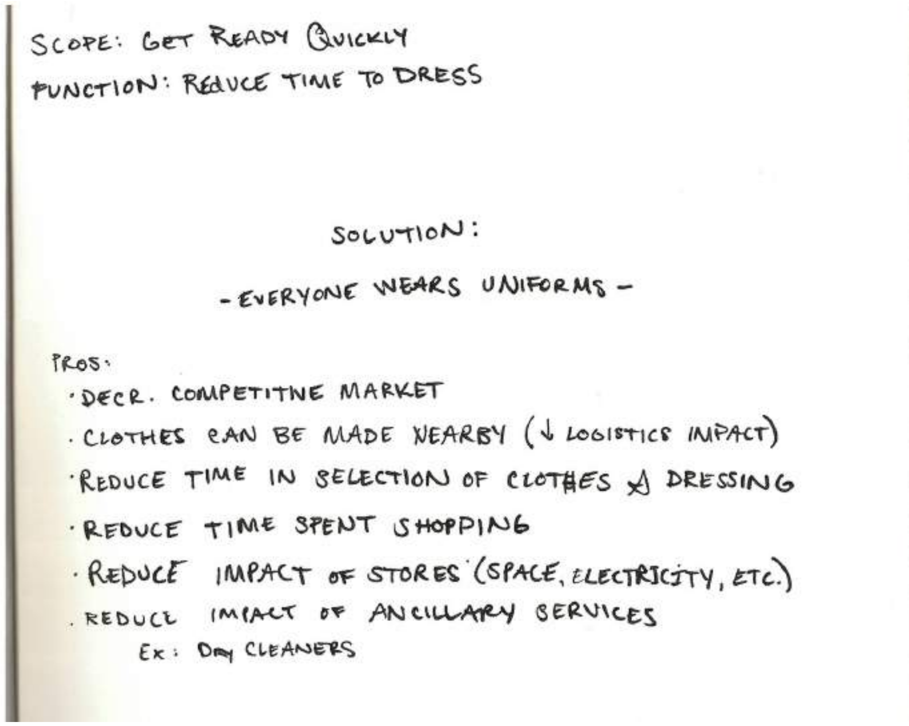

Figure 18: (Systems level lens) systems level solution to make getting ready in the morning more efficient and the clothing industry more sustainable [35]

From the generated concepts shown, it is clear that the students are generating a wider variety of innovative and sustainable solutions by virtue of brainstorming through the different lenses. While the course is still ongoing at the time of publication of this thesis, the teams will converge on one design and then make solid models, a marketing plan, and determine the life cycle environmental impact of the chosen design.

Conclusion

The following section will cover future changes to the SPD course, how to test the design process and the success of the course, and general impressions from both the 2015 and 2016 Sustainable Product Design Course,

(1) *General impressions of the 2015 and 2016 Sustainable Product Design course*

The following section is the general impressions and thoughts of how the both the 2015 and 2016 SPD course went. The impressions are those of Bryony DuPont, PhD. and Christopher Sharp, M.S. DuPont is an Assistant Professor of Mechanical Engineering at Oregon State University and she designed and has taught both the 2015 and 2016 course. Sharp is a PhD. Candidate at Oregon State University. He took the 2015 course, has helped with the design of the 2016 course, and has taught four of the 2016 course lectures.

Overall the 2015 design process flowed well, and by spending the majority of the course on the integrated product design (IPD) method, it made the students feel more creative during the concept generation process. However, the class did not feel focused on sustainability but instead the sustainability aspects of the course felt "forced". Because systems-level sustainability was not discussed it seemed very easy for students not consider systems-level sustainability in their final designs.

The 2016 course sought to improve integration of sustainable design thinking by focusing less on the integrated product design process and more on sustainable concept generation. Overall, this version of the class did not seem to flow as well as the previous year, but it did feel as though this setup—the 4 weeks of IPD and three weeks of Sustainable Design Methods—was more effective. By streamlining the IPD process and going through this content in fewer weeks, it left more time to focus on sustainable design. The structure of the 2016 course seemed to make the course less overwhelming for students and led to concept generation that was influenced by IPD but was focused on sustainability. The most significant improvement of the 2016 course is the way concept generation is performed, but it is yet unclear if it the most effective way to create sustainable and innovative products.

(2) *Testing the success of the product design method*

For future courses, the goal is to have more quantitative data on the effectiveness of the proposed design process. The effectiveness of the course on students learning will be assessed based on the specified educational objectives. One possible way to do this is to have students complete a survey at the beginning of the course and then complete the same survey at the end of the course and compare the results. This survey should be focused on the course objectives outlined in the syllabus. If students are able to correctly respond to the survey it could be concluded that the course objects were clearly communicated throughout the course and the students have successfully learned the objectives [23]. Alumni can also be surveyed to see if they are implementing the sustainable design practices they learned at OSU in their current work. Although all products are different, LCAs can be done on all products produced by the class. These results can be compared year to year to give an idea of the environmental impact of the created products, to gauge relative improvement in environmental sustainability as the course is improved.

(3) Possible Future Changes

In future versions of the course, there are plans to incorporate more high-tech methods and computational methods for sustainable product design. One example of this is the GREEn Quiz [22] which is an online survey that was created to help novice designers make sustainable design decisions. This method would be would be used as part of down-scoping before the lens lectures would begin. Research on sustainable design is still new and it is important as more information becomes available that it is integrated into design processes.

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Appendices

Appendix A: Materials Lens Lecture Slides

The Point

WHY DOES MATERIAL CHOICE MATTER?

Material Choice affects sustainability

Materials

Plastics
Bio-Plastics
Rubber
Steel
Aluminum
Copper
Glass
Wood
Leather
Wool
Plant Fibers
Composites (carbon fiber)

Plastics

Thermoplastic
s

Material	Energy to Produce	Recyclable?	Strengths	Weaknesses
Plastics	100 MJ/kg Accounts for 5% of crude oil consumption (see chart below)	Dependent on type of plastic	light weight high strength large range of colors	cannot always be recycled when recycled not as desirable contribute to large portion of household

01 PET	#1 PET(E)	Polyethylene terephthalate	Polyester fibers, soft drink bottles
02 PE-HD	#2 PEHD or HDPE	High-density polyethylene	Plastic bottles, plastic bags, trash cans, imitation wood
03 PVC	#3 PVC	Polyvinyl chloride	Window frames, bottles for chemicals, flooring, plumbing pipes
04 PE-LD	#4 PELD or LDPE	Low-density polyethylene	Plastic bags, buckets, soap dispenser bottles, plastic tubes
05 PP	#5 PP	Polypropylene	Bumpers, car interior trim, industrial fibers, carry-out beverage cups
06 PS	#6 PS	Polystyrene	Toys, flower pots, video cassettes, ashtrays, trunks, beverage/food coolers, beer cups, wine and champagne cups, carry-out food containers, Styrofoam
07 O	#7 O (OTHER)	All other plastics	Polycarbonate (PC), polyamide (PA), styrene acrylonitrile (SAN), acrylic plastics/polyacrylonitrile (PAN), bioplastics
ABS	#9 or #ABS[citation needed]	Acrylonitrile butadiene styrene	Monitor/TV cases, coffee makers, cell phones, most computer plastic
PA	PA[citation needed]	Polyamide	Nylon

6

Bio Plastics

Potatoes

Vegetable Oil

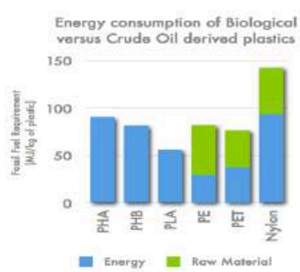
Wheat

Rice

Corn!

Tapioca

Traditional Plastics vs. Bio Plastic



Traditional Plastics vs. Bio Plastic

Energy Use of Bio Plastic vs Traditional Plastic

Type of Polymer	Petropolymer			Biopolymer		
Polymer	LDPE	PP	HDPE	PHB	PLA	TPS
Energy requirements (MJ/Kg-polymer)	81.8	85.9	73.7	44.7	54.1	25.4

Table 6: Energy requirements for polymer production.

CO_2 Emission of Bio Plastic vs Traditional Plastic

Type of Polymer	Petropolymer			Bioploymer		
Polymer	LDPE	PP	HDPE	PHB	PLA	TPS
CO_2 emissions (Kg CO_2/ Kg polymer)	3.0 Kg	3.4 Kg	2.5 Kg	2.6 Kg	1.8 Kg	1.14 Kg

Table 3: Carbon dioxide emissions for polymer production.

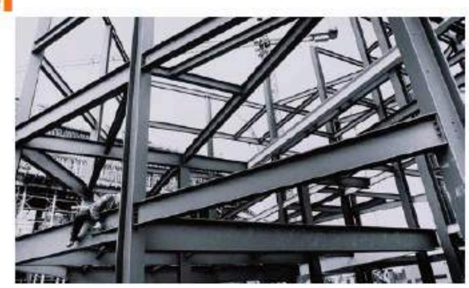
9

Rubber

Rubber cannot be recycled but can be upcycled

VIDEO:
https://www.youtube.com/watch?v=CKq42J7SaWw

Steel



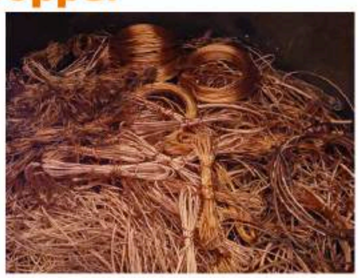
Recycling 1000 kg of steel saves roughly 1500 kg of ore, 500 kg of coal and 75% of the energy required to make primary steel

VIDEO: https://www.youtube.com/watch?v=-r1UisuNtHc

Aluminum

How it's made Video:
https://www.youtube.com/watch?v=fa6KEwWY9HU

Copper



Wire

Decoration

Copper

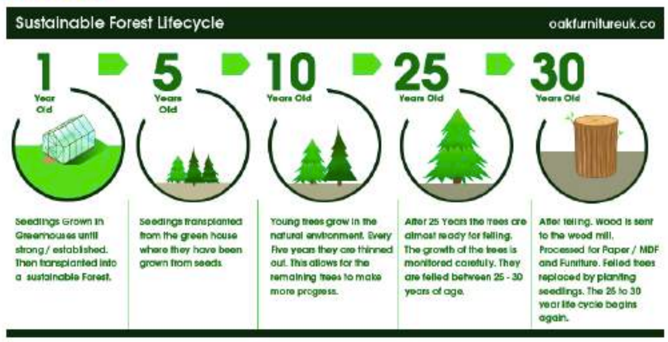
Money

14

Glass

VIDEO https://www.youtube.com/watch?v=dtxrtKd-Vao

Wood



Leather

How its made video: https://www.youtube.com/watch?v=9vbTCeYwt_g

Wool

How it is made:
https://www.youtube.com/watch?v=uEYsmzophTA

Plant Fibers

cotton

hemp

Jute

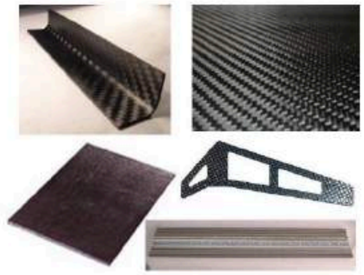
Flax

Plant Fibers

bamboo

video:https://www.ted.com/talks/elora_hardy_magical_houses_made_of_bamboo?language=en

Composites



Material	Embodied energy (MJ/kg)
Carbon fibre	183 to 286
Glass fiber	13 to 32
Polyester resin	63 to 78
Epoxy resin	76 to 80

Materials Selection Problem

Redesign a cast-iron skillet:

- understand environmental impact of cast iron
  - manufacturing
  - recyclable
    - yes but only at special sites
- think of function
  - conduct heat
  - non toxic even at high heat
- green skillets

https://www.cooksillustrated.com/equipment_reviews/1190-green-skillets

- Possible changes
  - geometry changes
    - smaller
    - rivet
  - other changes
    - material?

Materials Selection Problem

Redesign a Hammer:

- function
  - must be hard enough to hit metal without significant damage
  - must have a comfortable hand hold that allows for sufficient
- Changes
  - material
  - geometry
    - less metal material?

What material(s) is Iron Man's suit made of?

http://ironman.wikia.com/wiki/Mark_43

Iron Man's user needs

- **Bullet/impact resistant**
- **Heat resistant (uses thrusters for propulsion)**
- **Lightweight**
- **Easy to heal**
- **May need nuclear-specific materials**
- **Ability to maintain pressure**

Bullet/Impact Resistance

What material properties are indicative of bullet or impact resistance?

<u>Stiffness</u>

- Strength
- Geometry
- Hardness
- Toughness

What materials have high stiffness?

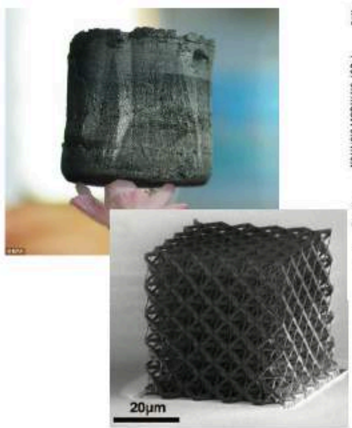
Heat resistant (uses thrusters for propulsion)

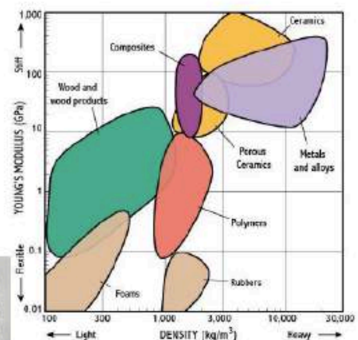
Thrusters are small jet engines in Iron Man's gloves and boots, used for propulsion. What materials will resist this heat?

Melting Point

Material	Melting Point °C
ABS	204
Tin	232
Silicone	300
PEEK	343
Aluminum	660
Bronze	1050
Nitinol	1310
Steel	1425
Iron	1538
Platinum	1768
Tungsten	3422
Ceramic	3870
Carbon	4492

Lightweight



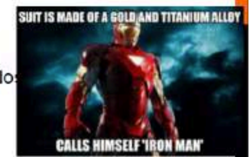


Tying it all together

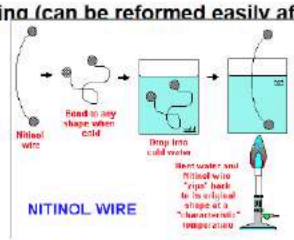
Bullet/Impact Resistant	Heat Resistant	Lightweight*
Metals	Nitinol	Polymers
Glass	Steel	Carbon
Kevlar	Ceramic	Ceramics
ABS	Carbon	*Geometry Dependent

What material is bullet/impact resistant, heat resistant, and can be made into lightweight geometries?

Nitinol



- **Nickel/Titanium alloy**
  - In the movies, he suggests it is Gold/Titanium…this is clo
- **High heat resistance**
- **High impact resistance, and**
  - Also has some flexibility in certain situations
- **Lightweight if used in sheet geometry**
- **Bonus: Self healing (can be reformed easily after being damaged)**



Appendix B: Materials Table

Materials table that was available to students after the materials lens lecture. All information is from Thompson's Sustainable Materials, Processes, and Production (The Manufacturing Guides) [36]

	Material	Energy to Produce	Recyclable?	Strengths	Weaknesses
1	Plastics	100 MJ/kg Accounts for 5% of crude oil consumption (see chart below)	Dependent on type of plastic	light weight high strength large range of colors	cannot always be recycled when recycled not as desirable contribute to large portion of household waste
2	Bioplastics	TPS: 25.4 MJ/kg plastic produce PHB: 44.7 MJ/kg plastic produced PLA: 7.4 MJ/ kg of plastic produced	Yes Sometimes Compostable	requires 20%-30% less energy than typical plastics to produce can be manufactured with conventional plastic forming equipment reduces the amount of solid waste in landfills	loses properties the more times they are recycled not necessarily sustainable could have a negative effect on food costs, deforestation, crop growth no bioplastics currently in commerci

					al use are fully sustainabl e
3	Rubber	67.6 MJ/kg	No	can be upcycled rubber trees (if properly managed) can last for 25 years	not many applications for shredded rubber
4	Steel	40 MJ/kg 284,000 liters of water per 1 ton of steel	Yes	can be recycled many times high strength relatively energy efficient	production accounts for 3% of global carbon dioxide emissions typically need to be coated to avoid corrosion production produces a lot of waste and hazardous byproducts
5	Aluminum	200 MJ/kg 88 liters of water per kg of aluminum	Yes	high strength to weight ratio	very efficient to recycle
6	Copper	60 MJ/kg	Yes	durable, long lasting and maintenance free	it takes about 1 ton of ore to make 1 kg of copper
7	Glass	30 MJ/kg	Yes	lower environmenta l impact than	fragile

				plastic	
8	Wood	17.6 MJ/kg	Yes	very low environmenta l impact 1 m^3 of tree growth absorbs 0.9 tons of CO_2	sustainability depends greatly on regional regulations
9	Leather	1669.37 litters of water per pound of beef 1 m^2 of leather results in 2/81 kg of CO_2 Tanning requires 340.69 litters/m^2, 0.5 kg of chemicals per 1 kg of leather	Yes	High value and commonly used	tanning uses a lot of energy environmental impacts depend heavily on the tannery
10	Wool	15.14 litters of water per kg of wool		water resistant fire resistant insulator water absorbent lower environmenta l impact than	wool production requires sheep production which can be environmental ly harmful and raises question on animal welfare

				synthetic fibers	
11	Plant Fibers		Yes	natural renewable strong	cotton is heavily sprayed with chemicals (more than 10% of agro-chemical consumption) requires certification to guarantee sustainability
12	Composites (carbon fiber)	275 MJ/kg http://www.rmi.org/RFGraph-Projected_energy_to_manufacture_CFRP	No	Very high strength to weight ratio	Production is slow and energy intensive about 5 times more energy intensive than steel

Appendix C: Manufacturing Lens Lecture Slides

The Point

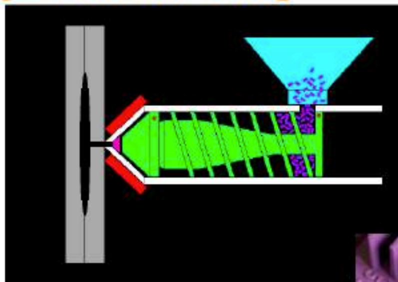
WHY DOES MANUFACTURING CHOICE MATTER?

The process by which a product is manufactured can greatly affect how sustainable that product is.

Four Types of Manufacturing Processes

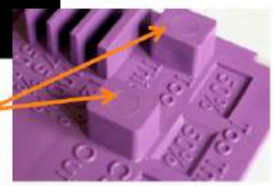
FORMING TECHNOLOGY

Injection Molding

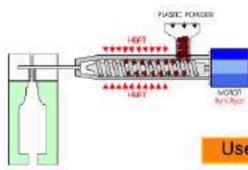


Used for both plastic thermosets and metals

Look for ejector pin marks



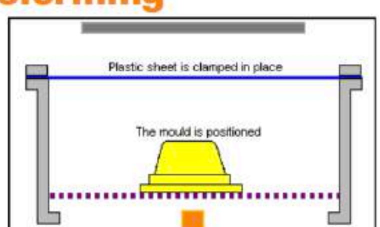
Blow Molding



Used for plastic

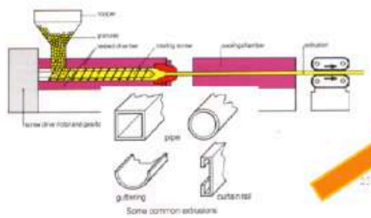
Look for parting lines from where the mold releases the part

Thermoforming



Used for plastics

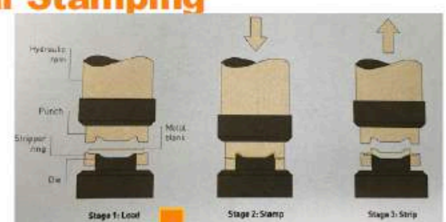
Extrusion



Used to make objects with constant cross section like pipes, gutters, and tubes

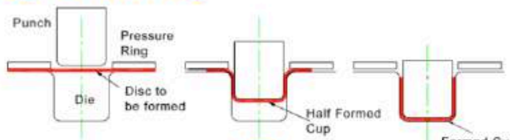
Used for both plastics and metals!
Works like a Play-Doh Fun Factory!

Metal Stamping



Subsequent bending/cutting operations can make for complex geometries

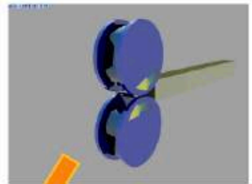
Deep Drawing



Used to make seamless cylinder geometries.

Forging

Forging



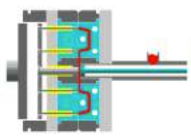
Roll Forging

Forging creates a favorable grain structure, so it makes very high-strength parts.

Used to manufacture metal

Die Casting

Pressure forces molten metal into reusable steel molds

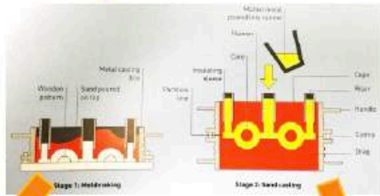


Can be used to make intricate geometries with thin walls and a nice surface finish

Die Casting

You cannot* Die Cast ferrous metals (like steel). Why? The molds are made out of steel, so molten steel + steel mold = disaster. Die Cast metal parts are often aluminum.

Sand Casting



Can be used for any metal. Can have rough surface features from the sand.

Investment Casting

Videos of Plastic Forming Processes

Blow Molding
https://www.youtube.com/watch?v=NE4c1gwzPb4

Extrusion
https://www.youtube.com/watch?v=wE_KTLIrdMA

Thermoforming
https://www.youtube.com/watch?v=65CcRHySqOU

Injection Molding
https://www.youtube.com/watch?v=eUthHS3MTdA

Vacuum Casting
https://www.youtube.com/watch?v=BqV_jsxD0UA

Compression molding
https://www.youtube.com/watch?v=SAUpN6zpSpQ

Videos of Metals Forming Processes

Metal Stamping
https://www.youtube.com/watch?v=5CuJjSk4U38

Forging
https://www.youtube.com/watch?v=mRA6RY2o9Lg

Die casting
https://www.youtube.com/watch?v=Pj_mjjUQad8

Deep Drawing
https://www.youtube.com/watch?v=IjBWH0Wdk3o

Roll Forming
https://www.youtube.com/watch?v=0CN2Foptu1k

Metal Injection Molding
https://www.youtube.com/watch?v=BGAKYSks_Wk&list=PLQyl1jXTi5lrgAu7XtoQoVQm-1OQ8MYml&index=12

Extrusion
https://www.youtube.com/watch?v=7qiDJ5U4uRc

Sandcasting
https://www.youtube.com/watch?v=K8SYhISGxN4

Investment Casting
https://www.youtube.com/watch?v=GWVli5iY8BI

Ceramics Forming Processes


Glass blowing

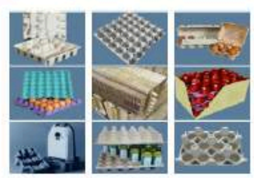

Clay throwing


Ceramic Slip Casting

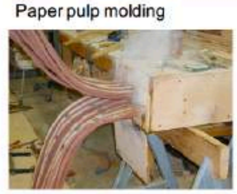
Ceramic Press Molding
https://www.youtube.com/watch?v=mjlW6aHZkv0

Wood Forming Processes


CNC Machining

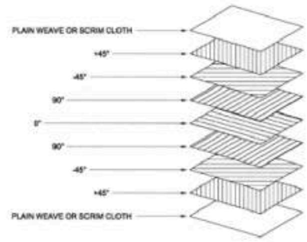

Paper pulp molding


Wood laminating


Steam Bending

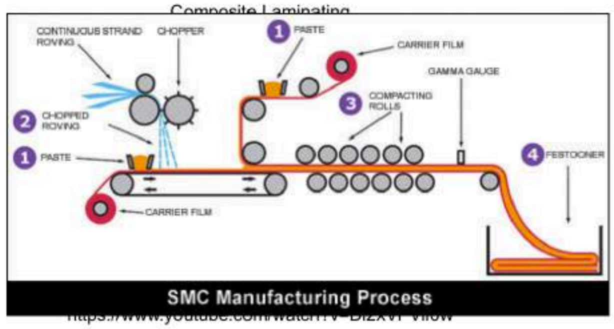
Composites Forming Processes

Composite Laminating

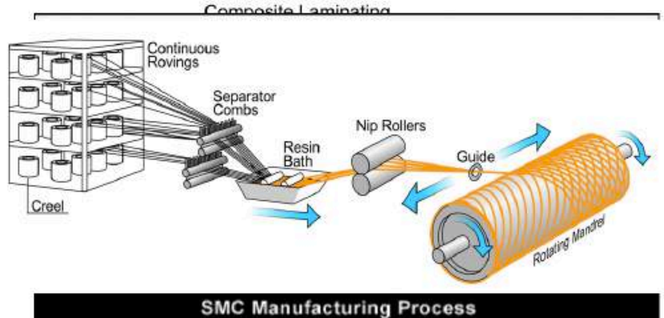


https://www.youtube.com/watch?v=Dl2xVPVif0w

Composites Forming Processes

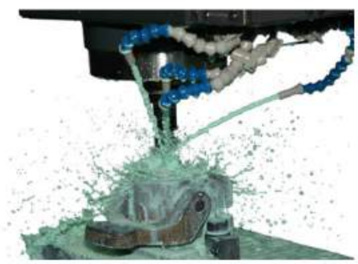


Composites Forming Processes



CUTTING TECHNOLOGY

Chemical Cutting



Thermal Cutting

Mechanical Cutting

JOINING TECHNOLOGY

Joining Technologies

Process that join materials together to form a product

- Welding
- Soldering
- Weaving
- Upholstery
- Timber frame structures

FINISHING TECHNOLOGY

Finishing Technologies

Processes that complete a product and get it ready for sale

- Painting
- Polishing
- Anodizing/Coating
- Applying labels

Eco-Indicator 99

Manufacturing Process	Indicator Value
Milling/Turning/Drilling Plastics*	6.4
Vacuum Forming	9.1
Cold Rolling into Sheet (Metal)	18
Injection Molding (Most plastics)	21
Pressing (Metal)	23
Sheet Production	30
Injection Molding (PVC)	44
Extrusion - Aluminum	72
Milling/Turning/Drilling Metal*	800
Brazing	4000

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Embodied Energy

Manufacturing Process	Energy Requirement Range (MJ/kg processed)			Source
Coventional Manufacturing				
Machining	5.3	-	7.5	[4]
Milling	1.3	-	2.6	
Grinding		8.8		[5]
Iron Casting	19	-	29	[3]
Sand casting	11.6	-	15.4	[6]
die casting		14.9		[7]
Forging		16.3		[8]
Finish Machining		24		[9]
Advanced Manufacturing				
Waterjet (Nylon)	150	-	214	
Waterjet (Steel)	167	-	238	[10]
Waterjet (Al)	195	-	1670	

http://web.mit.edu/ebm/www/Publications/9_Paper.pdf

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Appendix D: Manufacturing Tables

Forming Technology		Key:			
		Plastics	(pink)		
		Metals	(orange)		
		Ceramics	(green)		
		Wood	(blue)		
		Composites	(purple)		

Manufacturing Process [37]	**Cost** [37]	**Quality** [37]	**Suitability** [37]	**Environmental Impacts** [37], [38]	**Examples** [37]
Blow Molding: used to mass produce hollow containers → extrusion blow molding (EBM) → Injection Blow molding (IBM) → Injection stretch blow molding (ISBM)	Tooling: low Unit: low	high	high volume	all excess can be recycled	hollow bottles, containers look for: thin walls, parting lines
Thermoforming: manipulation of heated plastic sheets	Tooling: low to moderate Unit: low to moderate	dependent on material, pressure, and technique	Roll fed: batch → mass production Sheet fed: one-off → batch production	scraps can be recycled	take out containers, trays, drinking cups, briefcases
Vacuum	Tooling:	high	→	scrap cannot be	shatterproof

Casting: Similar to injection molding but for resins, two-part polymers, and thermosets, such as polyurethane. Instead of cooling in the mold, these thermosets cure in the mold.	low Unit: moderate		prototypes → one-offs, → low volume production	recycled	cases, headlight covers, mobile phone casings
Extrusion: Used to make parts with a constant cross section, where the dimensions of the cross sectional area are generally much smaller than the length.					
Injection Molding: video: https://www.youtube.com/watch?v=eUthHS3MTdA	Tooling: high Unit: low	very high	High volume production	scrap can be recycled	body and lid of TI-89, cheap sunglass frames look for ejector pin marks
Compression Molding: Rubber and thermoset plastic blanks are compressed in a mold with heat and pressure.	tooling: moderate unit: low	high strength high quality surface finish	Medium → high volume production	thermosets cannot be recycled	silicone keypads, O-rings with specialized geometry, complex parts made from elastomers
Metal	tooling:	high	High	scrap can be	metal sinks,

Stamping: Used to "punch" shapes and bends into a sheet of metal.	high Unit: low → moderate		volume production	recycled	metal cooking pots, electric motor casing
Deep Drawing Used to make seamless cylinder geometries. A punch impacts a metal blank in being held across the void of a die, forcing the metal upward/downward and outward to fill in the internal impression of the die.	Tooling: high to very high Unit: moderate	good	Medium to high volume production	all scrap material can be recycled	metal sinks, metal cooking pots, electric motor castings
Extrusion Metal blanks are fed through a die, and the resulting part has a constant cross section.					
Forging A blank of metal is heated and pressed in a die at extreme pressures	Tooling: high Unit: moderate	excellent grain structure → leads to very high strength parts	All types of production	all scraps can be recycled Energy Use: 16.3 MJ/kg [38]	tools, chain links, heavy-lifting tools
Roll Forming results in a long part with a constant cross section, but the	Tooling: high Unit: low to	good	Batch production	efficient use of energy and materials	tools, chain links, heavy-lifting hooks

initial material is in sheets, lending to open cross sectional geometries.	moderate				
Sandcasting Molten metal is poured into a mold made of compacted sand. When the metal cools. The sand mold is broken from around the part.	Tooling: Low Unit: Moderate	poor	One-off to medium production	up to 95% of mold material can be recycled after use Energy Use: 11.6 - 15.4 MJ/kg [38]	cast iron pans, church bells
Die Casting The metals are at a very high molten temperature, and they are injected into a mold at extremely high pressures	Tooling: high Unit: low	High quality surface finish variable mechanical properties	high volume production	all waste can be recycled Energy Use: 14.9 MJ/kg [38]	
Investment Casting A ceramic mold is created around a wax pattern, and when the ceramic is set, the wax is melted out of the cavity, and molten metal is poured in. When the metal cools, the ceramic mold is broken.	Tooling: low Unit: moderate → high	high	low to high volume production	all scrap can be recycled or reused	wedding rings, turbine blades, some gun parts

Metal Injection Molding (MIM) Similar to die casting but powdered metals are used	Tooling: high Unit: moderate → low	very high	high volume production	material can be recycled	steel gears, medical and dental equipment
Glass Blowing hollow and open-ended vessels are created involves blowing bubbles of air inside a mass of molten glass which is either gathered on the end of a blowing iron or pressed into a mold. Hollow and open-ended vessels are created	Tooling: high Unit: low	High	one-off to high volume production	glass and scrap can be recycled	food and beverage packaging, pharmaceutical packaging, and tableware and cookware
Lampworking forms hollow shapes and vessels through intense heat and craftsmen manipulation	Tooling: none Unit: high	High	One-off to batch production	glass and scrap can be recycled	jewelry, artwork, and scientific lab equipment
Clay Throwing done on a potter's wheel. creates symmetrical parts around an axis of rotation	Tooling: none Unit: low to moderate	quality varies	one-off to low volume production	scrap can be recycled before it is fired	gardenware, kitchenware, and tableware
Ceramic Slip	Tooling:	varies	low volume	scrap can be	bathroom

Casting A liquid clay body slip is poured into plaster molds and allowed to form a layer, the cast, on the inside cavity of the mold.	low Unit: moderate to high		and batch production	recycled before it is fired	whiteware, kitchen and tableware, lighting
Press Molding Ceramics manufactures multiple replica ceramic parts with the use of permanent molds	Tooling: low to medium Unit: low to medium	high	low to high volume production	no harmful byproducts	kitchen and tableware, sinks and basins, tiles
CNC Machining carried out on a milling machine, lathe, or router and results in a rapid precise and high quality end product	Tooling: low Unit: low	high	one-off to mass production	generates recyclable waste Energy Use: 24 MJ/kg [38]	automotive, furniture, tool making
Wood Laminating multiple sheets of veneer or solid timber are formed using molds and bonded together using very strong adhesives	Tooling: low Unit: moderate	high	one-off to medium volume production	less if wood is sources from renewable resources	architecture and engineered timber
Steam Bending strips of wood are steam	Tooling: low	good quality and high	one-off to high volume	low waste	boat building, furniture, musical

heated using a steam box the wood is then bent around a mold to create a specific shape	Unit: moderate to high	strength	production		instruments
Paper Pulp Molding http://www.instructables.com/answers/How-to-cast-pulp/	Tooling: low to moderate Unit: low to moderate	variable	batch and mass production	very low	biodegradable flowerpots, packaging
Composite Laminating fibers are combined together in desired formation and allowed to cure → wet lay-up → pre-impregnated with resin → resin transfer molding	Tooling: moderate to high Unit: moderate to high	high	one off to batch production	harmful chemicals are used so waste cannot be recycled	aerospace, furniture, racing cars
DMC and SMC Molding	Tooling: moderate Unit: low	high strength parts long fiber length	medium to high volume production	scrap cannot be recycled	automotive, building and construction, and electrical and telecommunication
Filament Winding The process involves winding	Tooling: low to moderate Unit:	high gloss surface finish	one-off to batch production	scrap cannot be recycled	aerospace, automotive, deep sea submersibles

filaments under tension over a rotating mandrel. The mandrel rotates around the spindle while fibers are laid down in the desired pattern or angle. Once the mandrel is completely covered to the desired thickness, the resin is cured.	moderate to high	high performa nce			
Rapid Prototyping Used to quickly fabricate a scale model of a physical part or assembly using three-dimensional computer aided design (CAD) data. Construction of the part or assembly is usually done using 3D printing or "additive layer manufacturing" technology.					

Cutting Processes [37]

Manufacturing Process	**Types**	**Environmental Impacts**	**Examples**
Chemical	→ photochemical machining: used		aerospace,

	to machine and mill thin sheet metals		automotive, electronics
Thermal	→ laser cutting: used to cut, etch, engrave, and mark sheet materials → electrical discharge machining: cut or erode metal through high voltage sparks		consumer electronics, furniture, model making, tool making
Mechanical	→ punching and blanking: shearing processes to cut internal and external shapes → die cutting: used to cut, perforate, score, and kiss thin sheet materials → water jet cutting: way to cut sheet metal using high pressure jet of water → glass scoring: precise method for cutting sheet glass		automotive, transportation, consumer electronics and appliances, kitchenware, packaging, promotional material stationery and labels, aerospace, scientific apparatus, glass pane, tiles, stained glass

Joining Processes [37]

Manufacturing Process	**Description**	**Environmental Impacts**	**Examples**
Arc Welding	→ encompasses a range of fusion welding processes → can only be used to join metals		containers, fabrications, structures
Power Beam Welding	→ joins materials by heating and melting the join interface → does not rely on the formation of an electric arc		aerospace, automotive, construction
Friction Welding	→ used to from permanent joints		aerospace, automotive and transportation, shipbuilding
Vibration	creates homogenous bonds in		automotive,

Welding	plastic parts by rapid linear or orbital displacement generating heat at the interface which melts the joint material and forms the weld		consumer electronics, packaging
Soldering and Brazing	form permanent joints by melting filler material between adjacent parts		electronics, jewelry, and kitchenware
Joinery	wood joint configuration		construction, furniture
Weaving	process of laying strips of material over and under each other to form an intertwined structure		furniture
Upholstery	process of bringing hard and soft components together to form one piece		furniture, automotive interiors
Timber Frame Structures			construction

Finishing Processes [37]

Manufacturing Process	**Description**	**Environmental Impacts**	**Examples**
Spray-painting	fast way to apply adhesive, primer, paint, lacquer, oil, sealant, varnish, and enamel		aerospace, automotive and transportation, consumer electronics and appliances
Powder Coating	used to coat metalwork powder adheres to piece electrostatically and is cured in an oven		automotive, construction, white goods
Anodizing	forming a protective oxidation layer on aluminum magnesium, or titanium		architecture, automotive, consumer electronics
Electroplating	application of a thin film of metal to another metal surface		consumer electronics, jewelry, furniture, automotive

Galvanizing	zinc coating steel or iron		architecture, bridges, automotive, furniture
Grinding, Sanding, and Polishing	sand, grind, or polish the surface of a material		automotive, cookware, glass lenses
Electropolishing	reverse of electroplating material is removed from the surface of a work piece		food processing, pharmaceuticals

Appendix E: Energy Use Lecture Slides

The Point

The energy that a product consumes throughout its life cycle contributes to its ecological footprint. Therefore it is important to understand the embedded energy of the products we create in order to make them more sustainable.

Energy Use by Sector

Energy consumption estimates by sector
trillion Btu

January to November	2015	2014	2013	2012
End–Use Sector				
Residential	18,932	19,401	18,802	17,931
Commercial	16,450	16,584	16,192	15,812
Industrial	28,460	28,872	28,652	28,251
Transporation	25,367	24,796	24,516	24,098
Primary Total	89,223	89,676	88,161	86,095

Source: U.S. Energy Information Administration, *Monthly Energy Review* – Table 2.1

Residential energy use accounts for about 21% of total US energy consumption

Examples of Products that are focused on reducing their energy footprint

Homegrown Project: Remade/Nokia First Phone/ Nokia Zero Waste Charger
charger reads how much energy the phone requires to charge and once it reaches that amount it turns off (pg. 44 product design)

Recompute computer cased in recycled cardboard instead of plastic (pg. 62 product design)

Inlet-Outlet
allows households to harness energy and give it back to the grid. Encourages use of solar panels and wind energy (pg. 52 product design)

Leaf
mobile phone that can be charged via solar energy (pg. 54 product design)

Examples of Products that are focused on reducing their energy footprint

RITI Printer
hand powered printer that uses coffee grinds as ink (pg. 64 product design)

GEnx Engine
airplane engine that reduces CO_2 emissions by 2 million tons per year (pg. 84 product design)

Product Life Cycle

http://www.solidworks.com/sustainability/docs/LCA_graphic_for_web.jpg
Johnson & Gibson (2014) Sustainability in Engineering Design
http://www.eioica.net/Method/LCA_Primer.html

6

Exercises: Coffee Maker

Embedded energy: 134-200 MJ/ functional unit

Materials: Plastic, glass

Manufacturing Process: Injection molding

Energy Use: 1000 to 1500 watts for 8-10 cups of coffee

Brainstorming: How can we redesign a coffee maker to make it more sustainable?

Appendix F: Biomimicry Lecture Slides

The Point

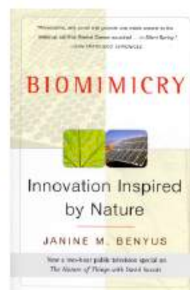
Many of our engineering questions have already been solved by nature. Although "biomimetic" does not inherently mean "sustainable", looking at how nature does things can lead to more sustainable design choices.

What is Biomimicry?

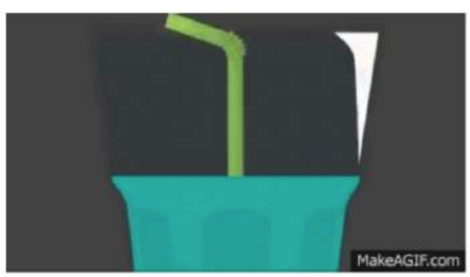
Biomimicry is being inspired by nature. It is using an idea found in nature and applying it, or taking nature's design principles and learning from them.

TED Talk:
https://www.ted.com/talks/janine_benyus_biomimicry_in_action

TED talk (12 Sustainable Design Ideas from Nature) Starts at 10:30
https://www.youtube.com/watch?v=n77BfxnVlyc

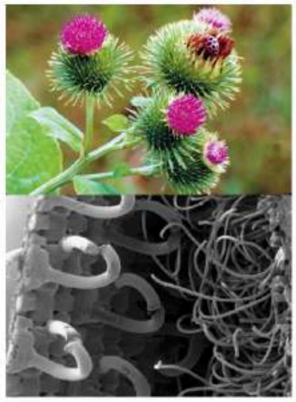


Examples: Capillary Action



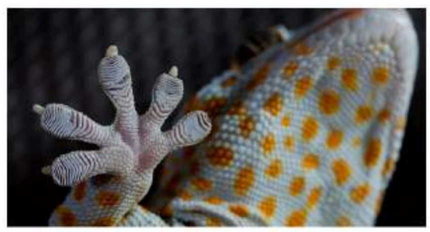
USGS defines capillary action as the movement of water within the spaces of a porous material due to the forces of adhesion, cohesion, and surface tension.

Example: Velcro



Velcro was modeled after the burrs on the Burdock Plant

Example: Adhesives (gecko feet)



Adhesive tapes can be modeled after gecko's feet and their ability to stick to almost anything

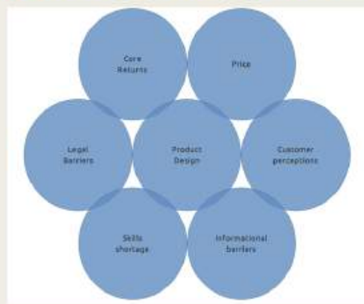
https://www.youtube.com/watch?v=JnBkbaFsZOY

Appendix G: Upcycling/ Remanufacturing Lecture Slides

What is Upcycling and Remanufacturing

- **Upcycling** is the process of converting an old discarded product into something new and useable [26].
- **Remanufacturing** is the process of returning a used product to its original state [27].

Challenges with remanufacturing



There are many challenges associated with remanufacturing but at the heart is product desing.

A product must be deisgned to be remanufacutred. This includes designing products for disassembly with components that can be easily replaced and tested.

Deisgn For Disassembly

The Basics:

Minimize the number of fasteners
Minimize the number of fastener removal tools needed
Fasteners should be easy to remove
Fastening points should be easy to access
Snap fits should be obviously located and able to be torn about using standard tools
Try to use fasteners of material compatible with the parts connected
If two parts cannot be compatible, make them easy to separate
Eliminate adhesives unless compatible with both parts joined
Minimize the number and length of interconnecting wires or cables used
Connections can be designed to break as an alternative to removing fasteners

Note: Easy assembly does not always equal easy disassembly

Design for Easy Disassembly – Apple MacBook Pro

- Can be disassembled by hand and with a Phillips screwdriver (no permanent fasteners)
- Each modular subassembly (hard drive, battery, fan, logic board, optical drive, etc.) can be removed easily without potential damage or affecting other components(for re-use)
- Body is made from a single block of aluminum, all scrap is reused
- Components are easily disassembled into pure material streams, such as the glass screen, the aluminum body, and the plastic keys
- Example of a partially cradle-to-cradle design

http://www.ifixit.com/Teardown/MacBook-Pro-13-Inch-Unibody/814/1
http://www.ifixit.com/Teardown/MacBook-Pro-13-Inch-Unibody/814/1

Design for Remanufacturing

Remanufacturing: End-Of-Life strategy

- *Product is returned and disassembled*
- *Parts are sorted, cleaned, and inspected*
- *Quality and performance are certified*
- *Parts are re-entered into the manufacturing part supply stream*

XEROX®

- *Remanufactured 30,000 tons of returned machines (1997)*
- *Kept four million cubic feet of materials out of landfills*

→ That's 250 family homes worth of material

Otto, K. and Wood, K., (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall
http://www.xerox.com/downloads/usa/en/e/ehs_remanufacture_2005.pdf

Disassembly and Cradle to Cradle

While some products are being designed specifically to be re-used and recycled (cradle-to-cradle)

- *Like your old Macbook Pro*
- *Or Kodak disposable cameras*

Others are specifically designed to be

disposed of at end-of-life (cradle-to-grave)

- *Cheap electronics that purposely cannot be fixed by a layperson*
- *Consumer products that include permanent fixtures/welds or highly specialized tooling to impede access to interior mechanisms*
- *Products made of non-recyclable materials or materials that cannot be separated*
- *Designs that must include destruction of a component in order to disassemble*
- *Components that include hazardous chemicals that cannot be captured for re-use*

http://store.kodak.com/store/ekconsus/en_US/pd/Power_Flash_Single_Use_Camera/productID.164408000

Appendix H: Systems Level Lecture Slides

The Point

To understand sustainability on a systems level

Example: Car

https://www.linkedin.com/pulse/subaru-proud-have-3-its-cars-top-ten-2015-picks-autobeiacg-consulting

Materials

What types of materials are cars made of?

https://www.allianz.com.au/car-insurance/infographic/materials-used-to-make-a-car-infographic

Materials

Wha
cars

https://www.allianz.com.au/car-insurance/infographic/materials-used-to-make-a-car-infographic

Materials

Could you choose different materials that are more sustainable?

https://www.allianz.com.au/car-insurance/infographic/materials-used-to-make-a-car-infographic

Manufacturing

How is a car made?
https://www.youtube.com/watch?v=FQ9zmJCBlaw

http://www.thehindubusinessline.com/companies/car-sales-down-125-bikes-up-48-in-dec/article4289995.ece

Manufacturing

?

Can you think of any ways to change the manufacturing processes that will reduce the impact?

http://www.thehindubusinessline.com/companies/car-sales-down-125-bikes-up-48-in-dec/article4289995.ece

Energy Use

What is the largest energy impact in a cars life cycle?

http://www.cardirectvirginia.com/blog/gas-station/
https://www.eia.gov/tools/faqs/faq.cfm?id=23&t=10

Energy Use

2015, about 140.43 billion gallons of gasoline were consumed in the United States

http://www.cardirectvirginia.com/blog/gas-station/
https://www.eia.gov/tools/faqs/faq.cfm?id=23&t=10

Biomimicry

Are they ways to apply biomimicry principles in car design

https://bridgeresearchagency.files.wordpress.com/2012/09/biomimicry-bionic-car.jpg

Biomimicry

Car design based on boxfish
Acceleration: 62 mph in 8.2 seconds
Fuel Economy: 70 mpg city/highway

https://bridgeresearchagency.files.wordpress.com/2012/09/biomimicry-bionic-car.jpg

Upcycling/ Remanufacturing

Can cars be recycled? Are their was to remanufacture car or design them for disassembly?

http://usedautopartsdenver.co/userfiles/661/images/wagonparts.jpg

What is the function of a car?

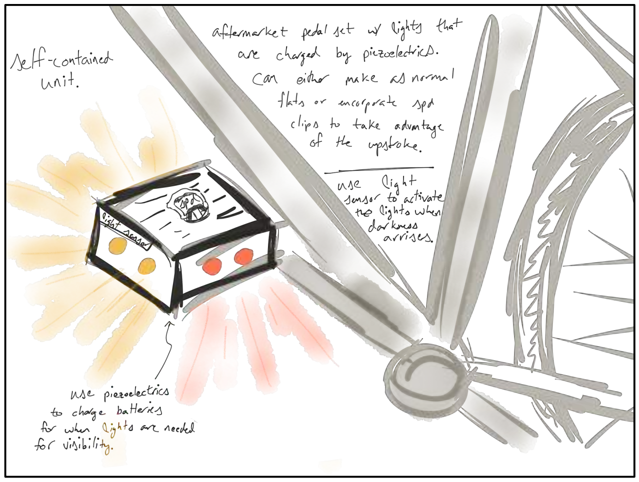
To get people from one place to another (like this fish)

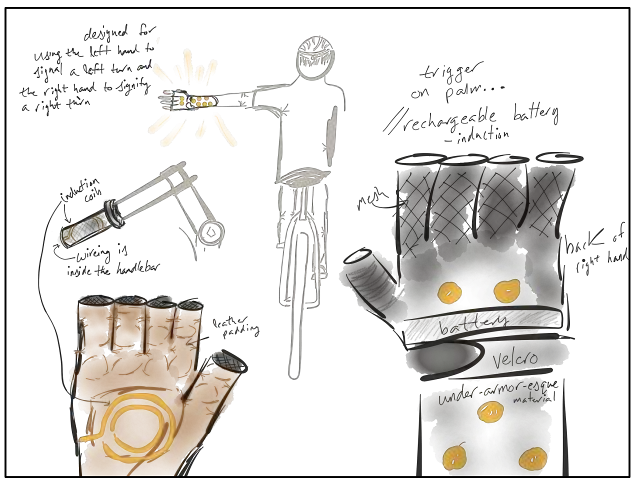
http://i.imgur.com/ZRdltGP.jpg

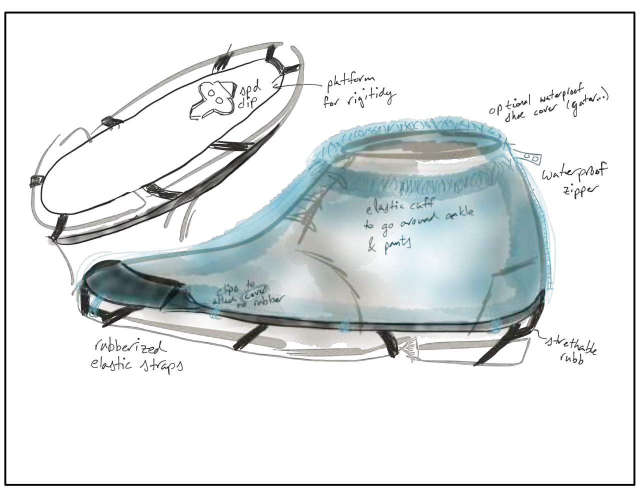
Is a car the best solution to fix that function?

Appendix I: 2015 Sustainable Product Design Student Concepts

The following concepts from the 2015 Sustainable Product Design Course. All concepts are from the team designing for the "Getting to Campus" scope [33].

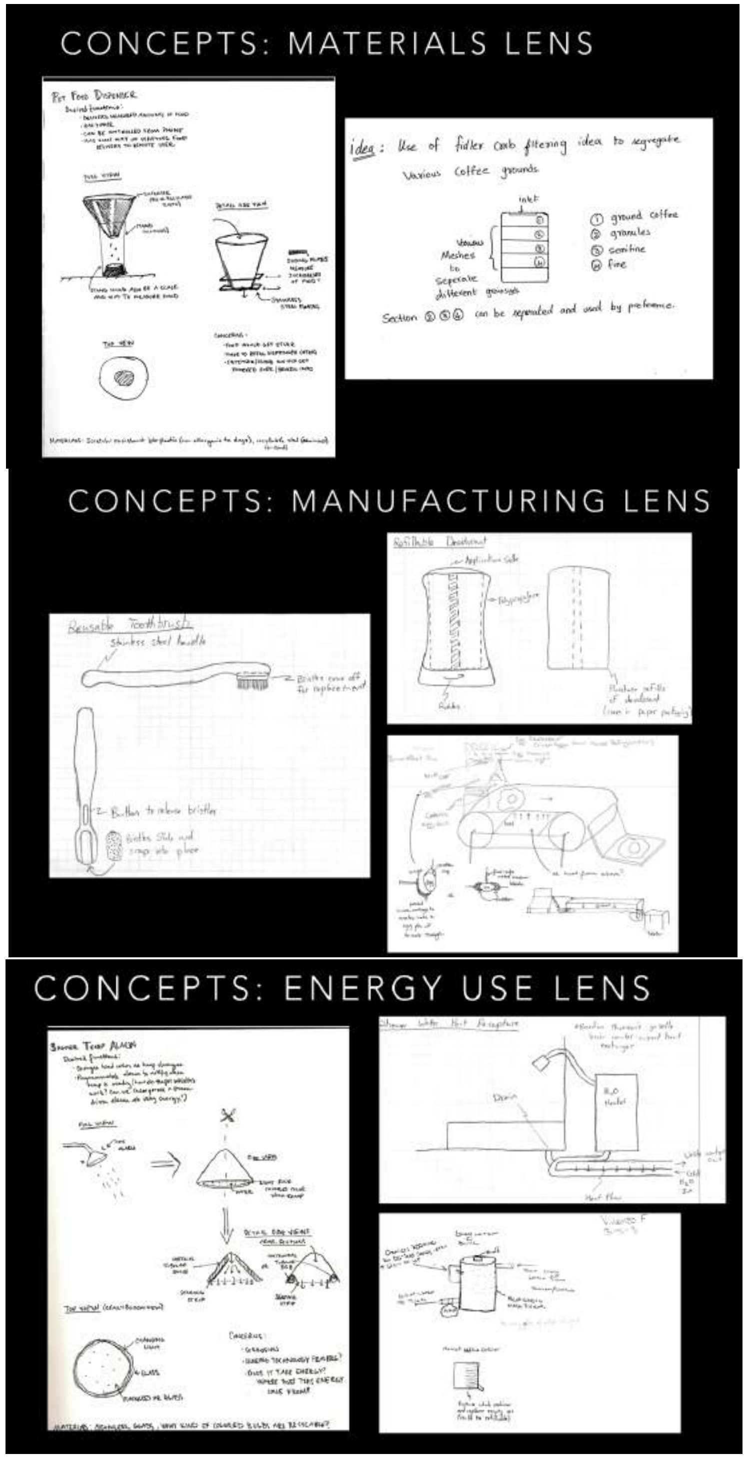


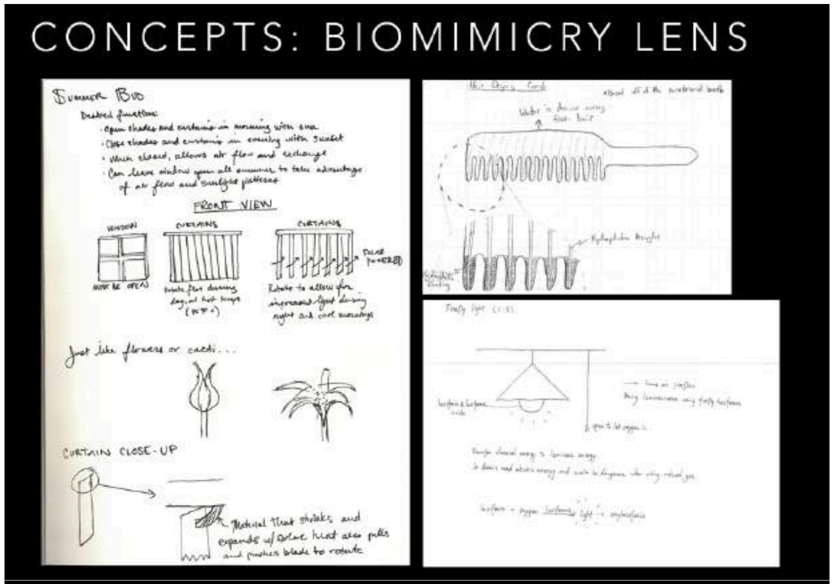


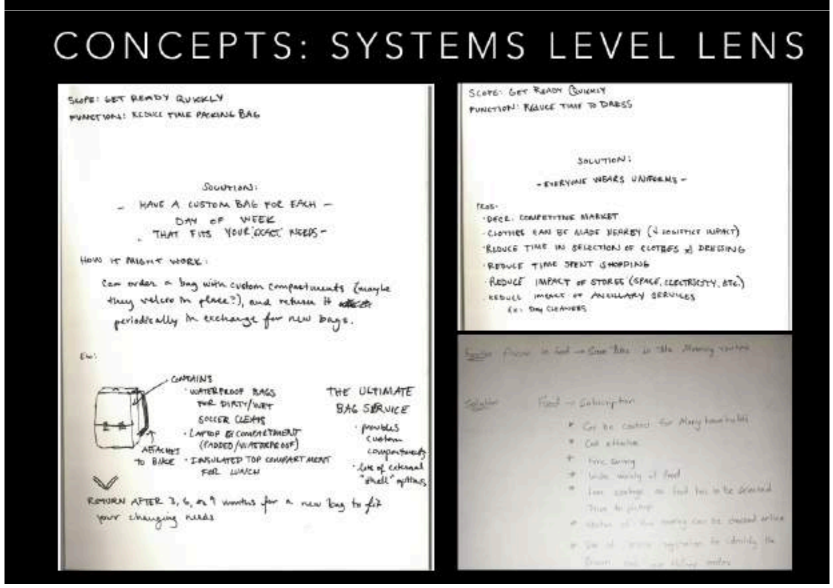


Appendix J: 2016 Sustainable Product Design Student Concepts

The following concepts are from the 2016 Sustainable Product Design Course. All concepts are from the team designing for "The Best Part of Waking Up" scope [35].




CONCEPTS: BIOMIMICRY LENS
Summer Bud
Desired functions:
· Open shades and curtains in morning with sun
· Close shades and curtains in evening with sunset
· When closed, allows air flow and exchange
· Can leave window open all summer to take advantage of air flow and sunlight patterns
FRONT VIEW
WINDOW
CURTAINS
CURTAINS
Just like flowers or cacti...
CURTAIN CLOSE-UP
Material that shrinks and expands w/ solar heat also pulls and pushes blade to rotate


CONCEPTS: SYSTEMS LEVEL LENS
SCOPE: GET READY QUICKLY
FUNCTION: REDUCE TIME PACKING BAG
SOLUTION:
- HAVE A CUSTOM BAG FOR EACH DAY OF WEEK THAT FITS YOUR NEEDS -
HOW IT MIGHT WORK:
Can order a bag with custom compartments (maybe they velcro in place?), and return it periodically in exchange for new bags.
CONTAINS
· WATERPROOF BAGS FOR DIRTY/WET SOCCER CLEATS
· LAPTOP COMPARTMENT (PADDED/WATERPROOF)
· INSULATED TOP COMPARTMENT FOR LUNCH
ATTACHES TO BIKE
THE ULTIMATE BAG SERVICE
RETURN AFTER 3, 6, or 9 months for a new bag to fit your changing needs
SCOPE: GET READY QUICKLY
FUNCTION: REDUCE TIME TO DRESS
SOLUTION:
- EVERYONE WEARS UNIFORMS -
REDUCE TIME SPENT SHOPPING