PRODUCT DESIGN FOR REPAIRABILITY: IDENTIFYING FAILURE MODES WITH TOPIC MODELING AND DESIGNING FOR ELECTRONIC WASTE REUSE

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ABSTRACT

Product Design for Repairability: Identifying Failure Modes with Topic Modeling and Designing for Electronic Waste Reuse

Claire Joelle Franz

Design for repairability is imperative to making products that last long enough to justify the resources they consume and the pollution they generate. While design for repairability has been gaining steady momentum, especially with recent advances in Right to Repair legislation, there is still work to be done. There are gaps in both the tools available for repair-conscious designers and the products coming onto store shelves. This thesis work aims to help set sails in the right direction on both fronts.

This research explores the use of topic modeling (a natural language processing technique) to extract repairability design insights from online customer feedback. This could help repair-conscious designers identify areas for redesign to improve product repairability and/or prioritize components to provide as available replacement parts. Additionally, designers could apply this methodology early in their design process by examining the failure modes of similar existing products.

Non-Negative Matrix Factorization (NMF) and BERTopic approaches are used to analyze 5,000 Amazon reviews for standalone computer keyboards to assess device failure modes. The proposed method identifies several failure modes for keyboards, including keys sticking, legs breaking, keyboards disconnecting, keyboard bases wobbling, and errors while typing. An accelerated product design process for a keyboard is presented to showcase an application of the topic modeling results, as well as to demonstrate the potential for product design that uses a “piggybacking” design strategy to reuse electronic components. This work indicates that topic
modeling is a promising approach for obtaining repairability-related design leads and demonstrates the efficacy of product design to reduce e-waste.

Keywords: design-for-repairability, data-driven design, online reviews, customer feedback, topic modeling, product design, sustainability, electronic waste reuse, e-waste
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1. INTRODUCTION

1.1 PROJECT MOTIVATION

Electronic waste is environmentally costly for multiple reasons. The materials and manufacturing processes used to make consumer electronics have a significant carbon footprint. This comes from the $CO_2$ emitted throughout the product life cycle, from mineral mining to end-of-life recycling. This results in embodied carbon in consumer electronics like laptops, cell phones, and tablets [1]. In 2020, an estimated 580 million metric tons of greenhouse gas emissions were from information and communications technology (ICT) devices, which was a 53% increase from the emissions in 2014. Another 50% increase is predicted by 2030 if current trends continue [2]. Additionally, 80% of e-waste ends up in landfills, forming mountains of hazardous waste where toxins pollute both soil and drinking water [3], [4].

The United States commonly exports this waste to developing countries, many of which do not have the necessary facilities or labor to extract value from these products. This poses a burden to the developing world, further widening the environmental inequality gap [2], [4]. Additionally, the metals required for electronics manufacturing (such as tin, cobalt, and gold) often come from mines in developing countries that offer workers (including children) inhumane conditions in exchange for less than a living wage [5]. This reality paints a gloomy picture of a complex problem that requires global collaboration across industries. This work will present one of the primary ways designers can make a difference: designing products to be easily repairable, referred to as design for repairability [4].

The best way to keep electronics out of landfills is to continue using them. For consumers, this means repairing the devices they already own instead of replacing them. For designers, this means avoiding planned obsolescence and opting instead for designs that prioritize modularity, ease of disassembly, and the availability of replacement parts and device documentation [6]. In
this thesis, repair is defined as restoring a product by replacing a component or otherwise mending what is torn or broken [7]. Reuse is defined as using a product again, especially after refurbishing or transforming it [8].

The Right to Repair movement aims to make repairable design practices commonplace, empowering consumers to fix their own devices instead of being forced to send them in for service or buy new ones altogether [9]. As of the beginning of 2024, twenty-seven U.S. states have some form of Right to Repair legislation [10]. In 2023, California, home to Silicon Valley, enacted legislation that requires manufacturers to “provide the means to diagnose, maintain or repair for seven years for products with a price point more than $100; three years for products under $100” [11]. The increasing prevalence of legislation such as this and growing momentum for the Right to Repair movement makes design tools for repairability even more desirable.

1.2 PROBLEM STATEMENT

While many principles of design for repairability can be widely applied, there is a lack of device-specific design tools. For repair-conscious designers, it may require extensive analysis and/or testing to identify common failure modes in the early stages of product development. In order to add design for repairability practices to already tight design timelines, there needs to be a streamlined approach that begins at concept ideation. Conveniently, customer feedback from online reviews provides an under-utilized source of insight for designers. Research is needed to explore natural language processing (NLP) methods for turning product reviews into repairability design insights.

A second problem is the societal shift towards excessive consumerism, especially in the United States, and the design for obsolescence philosophy that has plagued many consumer products. There is often little consideration for the environmental impact of the products we use every day, and “sustainably made” labels (often greenwashed) are quick to thwart concern. The average
consumer spends little attention on repair and much more attention on quickly replacing broken devices or torn clothes with new and improved models or stylish garments. Addressing these issues requires a mindset shift towards conscious consumption and a more strategic use of resources. From a product design perspective, there is an opportunity for designs that are not only repairable and built to last, but also make clever reuse of resources, especially electronic components.

1.3 PROJECT OBJECTIVES

This project has two main objectives to address the problem statement:

1) Examine if repairability design insights can be obtained from online customer reviews using natural language processing (NLP) techniques. Specifically, how can topic modeling help identify target areas for product design to improve device repairability and/or indicate components to prioritize as available replacement parts? To answer this question, topic modeling is applied to Amazon product reviews to identify failure modes linked to specific electronic devices. Standalone computer keyboards are examined in this research as a case study.

2) Present an accelerated product design case study where failure mode findings from topic modeling are applied to standalone computer keyboard design. Additionally, to address the second problem described in the problem statement, electronic components from existing waste keyboards will be reused to model a “piggybacking” design strategy. In this context, “piggybacking” refers to a design approach that adds components to an existing product to extend the total product lifespan [12].
2. BACKGROUND

2.1 DESIGN FOR REPAIRABILITY

2.1.1 REPAIRABLE DESIGN GUIDELINES

The fundamental goal of repairable design is to make it as easy as possible for consumers to fix their own electronics. This requires consideration throughout the product design process, from early design decisions that create modular components all the way to making sure device documentation, repair guides, and replacement parts are available after product launch. According to the repair experts at iFixit, “highly repairable devices” should be designed to 1) “disassemble and reassemble, nondestructively and reversibly,” 2) involve only easily available tools for repair, and 3) prioritize access and repair of components that are either critical for device functionality or most likely to need repair [13].

The third criterion for highly repairable devices often requires specific knowledge about the performance of the device itself or similar existing products. The methodology proposed in this thesis aims to help designers obtain these insights through customer feedback. In addition to making use of specific insights, there are many design for repairability practices that can be widely applied across different devices.

Design practices to enhance product repairability include, but are not limited to:

- Employ a modular design, allowing for easy component repair, upgrade, and recycling [1], [12], [13], [13], [14], [15].
- Use forward-thinking design approaches for components with fast evolutionary speeds (i.e., those that become obsolete the fastest) to enable future upgrades [12], [14].
- Use fasteners or magnets instead of adhesives whenever possible [12], [13], [15].
- Choose standard fasteners that can be removed with common tools [13], [15].
- Prioritize using off-the-shelf components instead of custom parts [13].
- Structure the device to minimize the number of steps it takes to remove critical components such as batteries [13], [15].
- Include identifying marks on devices to indicate key assembly information (such as arrows indicating proper orientation, labels for device make and model to enable online research, etc.) [13], [15].
- Provide a device service manual with replacement instructions for critical components, troubleshooting recommendations, necessary schematics and diagrams, etc. [13], [15].
- Ensure availability of reasonably priced device replacement parts from the original manufacturer or a trusted third party [13], [15].
- Use standard connection ports [12].
- Use separable snap-fits instead of fused plastic [12], [15].
- Design high-quality, durable products that people will want to repair and continue using [15].

2.1.2 EXAMPLES OF REPAIRABLE CONSUMER ELECTRONICS

There are an increasing number of consumer electronics that are highly successful at modeling and implementing design for repairability practices. A couple devices worth studying as gold standard examples for repairability (as evaluated by iFixit) are the Framework Laptop 13 and the Fairphone 5. Both of these devices received a 10/10 repairability score from iFixit [16], [17].

Framework, a California based company, sells laptops that prioritize modularity and repairability. Framework computers are engineered to be as easily upgradable and repairable as possible [18]. It only requires 5 screws to detach the top cover on the Framework Laptop 13, after which the user has easy access to replacing the battery, adding more RAM or storage, and even changing out the motherboard. Almost everything about the laptop is modular (including the bezel and
input port modules) and replacement parts are readily available on the Framework website. The Framework Laptop 13 is shown in Figure 1.

Figure 1. Framework Laptop 13 [19].

The Amsterdam-based company Fairphone currently sells smartphones, over-ear headphones, and wireless earbuds. The Fairphone 5 offers a modular design with replacement parts (including displays, batteries, cameras, ports, speakers, etc.) available for purchase online. The phone also has a 5 year warranty, drawing attention to the brand’s commitment to long-lasting products instead of the yearly upgrade plans we often see advertised [20]. The Fairphone 5 is shown in Figure 2.

Figure 2. Fairphone 5 [21].
The Framework Laptop 13 and Fairphone 5 are both exemplary models of consumer electronic design that prioritizes repairability to deliver an excellent customer experience and minimal environmental impact.

2.2 KEYBOARD BACKGROUND INFORMATION

2.2.1 TYPES OF KEYBOARDS

There are a variety of different types of keyboards that have been developed since the first computer keyboards evolved from typewriters in the mid-to-late 1900s [22]. An inexhaustive list of different categories of keyboards includes mechanical keyboards, membrane keyboards, topre switch keyboards, and buckling spring keyboards. Within the category of membrane keyboards are a variety of rubber dome style keyboards, including scissor switch keyboards, butterfly switch keyboards, and chiclet keyboards [23], [24].

For the context of this work, the distinction between mechanical and membrane keyboards is most relevant. These are the two most common types of keyboards in circulation today. Broadly speaking, mechanical keyboards have mechanical switches, i.e. switches with a spring mechanism where physical motion touches metal contacts together and closes a circuit [23], [25]. On the other hand, membrane keyboards use conductive traces on film membranes that register a key press when pushed together [23], [26].

2.2.2 HOW THEY WORK

Standalone computer keyboards, while straightforward in their use case, are intricate electromechanical devices. This section will describe how mechanical and membrane keyboards work. Figure 3 gives an overview of keyboard anatomy and useful terminology.
Mechanical and membrane keyboards differ in their structure and the mechanism by which a finger press translates to a letter appearing on screen. Basic mechanical keyboard components include keycaps, switches, stabilizers, a baseplate, a printed circuit board assembly (PCBA), gaskets, foam, and a housing of some kind (top and/or bottom). Mechanical keyboard enthusiasts may opt for additional modifiers as well, such as sound dampening foam or O-rings [28]. Figure 4 provides an overview of mechanical keyboard components.

Figure 3. Keyboard Anatomy and Terminology [27].

Figure 4. Mechanical Keyboard Components [29].
Arguably the most interesting aspect of the mechanical keyboard is the switch. Switches are an assembly of sub-components, including an upper housing, stem, metal contacts, spring, lower housing, and PCB mount legs that insert into the keyboard PCBA. These components are shown in Figure 5.

![Figure 5. Mechanical Switch Assembly](image)

For traditional mechanical switches, pressing down on a keycap compresses a spring and allows two thin metal (often gold-plated) contact leaves to come together. The metal contacts close the switch circuit and provide an electrical signal that indicates a key has been pressed [23], [25]. The contacts only touch during a key press because the downward motion clears an extrusion on the stem out of the way. This mechanism for switch actuation is illustrated in Figure 6. The image on the left shows the contacts blocked by the extrusion on the stem. On the right, the stem and extrusion have been moved down as the key is pressed, allowing the contacts to touch.

![Figure 6. Mechanical Switch Actuation](image)
There are many different types of switches that vary in both feel and sound. Switches are broadly broken up into three categories: linear, tactile, and clicky. Linear switches have a linear relationship between the actuation force and spring compression, leading to a smooth typing experience. Tactile switches have a “bump” of extra resistance midway through the typing stroke, meaning additional force is required to fully actuate the switch. This provides additional feedback, which some users find useful for typing (to reduce mistypes) but disadvantageous for gaming (where speed is important). Clicky switches are similar to tactile switches, though they also have an added clicking sound with each key press [31].

The most common mechanical switches are Cherry MX switches, which come from the well-established German electronics company Cherry. Cherry started manufacturing computer keyboards in 1973 and obtained the first patent for a keyboard switch the same year. Today, after the expiration of their MX switch patent from 1983, there are a variety of competitors to Cherry making similar switches or their own versions [32]. These include Gateron, Logitech, Razer, Corsair, and more [31]. Generally, switches are named with colors that indicate their performance. For instance, Gateron regular switches (used later in this project) include seven color switches, each with different qualities [33]. These are outlined in Figure 7.

<table>
<thead>
<tr>
<th>Type</th>
<th>Operating force</th>
<th>Pre-travel</th>
<th>Travel distance</th>
<th>Sound level</th>
<th>Feel</th>
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<tr>
<td>Red Switch</td>
<td>Linear</td>
<td>45 ±15 gf</td>
<td>2.0 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Low</td>
</tr>
<tr>
<td>Brown Switch</td>
<td>Tactile</td>
<td>55 ±15 gf</td>
<td>2.0 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Medium</td>
</tr>
<tr>
<td>Blue Switch</td>
<td>Clicky</td>
<td>60 ±15 gf</td>
<td>2.3 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Loud</td>
</tr>
<tr>
<td>Black Switch</td>
<td>Linear</td>
<td>60 ±15 gf</td>
<td>2.0 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Low</td>
</tr>
<tr>
<td>Yellow Switch</td>
<td>Linear</td>
<td>50 ±15 gf</td>
<td>2.0 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Low</td>
</tr>
<tr>
<td>Green Switch</td>
<td>Clicky</td>
<td>80 ±15 gf</td>
<td>2.3 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Loud</td>
</tr>
<tr>
<td>White/Clear Switch</td>
<td>Linear</td>
<td>35 ±15 gf</td>
<td>2.0 ±0.6 mm</td>
<td>4.0 mm Max.</td>
<td>Low</td>
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Figure 7. Gateron Switch Colors [33].
Keycaps are also highly customizable within the mechanical keyboard industry, offering consumers a variety of different materials, designs, and keycap profiles. Keycaps are most commonly made from injection-molded plastic, usually either acrylonitrile butadiene styrene (ABS) or polybutylene terephthalate (PBT) [27]. However, specialty keycap sets are available in a range of materials, including wood, metals, epoxy resin, and more. There are also a range of keycap profiles for consumers to choose from. Different profiles are optimized for speed, ergonomic comfort, etc. Examples of common keycap profiles are shown in Figure 8.

![Figure 8. Common Keycap Profiles](image)

Membrane keyboards have the same basic anatomy as mechanical keyboards (see Figure 3) but differ greatly in their functionality (as well as in price point and customization options). Instead of a full-size PCBA baseplate that attaches to the metal connectors of switches, membrane keyboards consist of plastic film sheets with conductive traces. There is some variety in arrangement across devices, but typically there is a top sheet, a spacer sheet, and a bottom sheet [23], [26]. The components of a membrane keyboard are illustrated in Figure 9.
When the conductive trace on the top sheet is pressed down against the conductive trace on the bottom sheet, the circuit is completed and a key press is registered. Rubber dome membrane keyboards have rubber domes to transmit the actuation force from the keycap to the film sheets. After the rubber is pressed down, it naturally pops back up again, without the need for a mechanical spring [23]. Typically, these rubber domes are arranged together in a flexible rubber sheet.

Both mechanical and membrane keyboards use a matrix (either arranged on a PCBA or conductive traces) that allows the keyboard microcontroller to identify which key has been actuated using a look-up table. Once the keyboard encoder transmits this information to the host computer, the character appears on screen [35], [36]. This process repeats quickly and repetitively for each key press (94 times in this sentence!).

Figure 9. Membrane Keyboard Components [34].
2.2.3 REPAIRABILITY COMPARISON

Mechanical keyboards are generally more repairable than membrane keyboards. This is mostly because of their higher price point—consumers are not expecting a disposable device. The higher price point also means replacement components are a smaller fraction of the total device value, making repair more economically attractive to consumers. According to Carsten Frauenheim, Repairability Engineer at iFixit, consumers are usually only willing to spend about 25-30% of the device value on repair. This explains why so many membrane keyboards are quickly discarded. Even if reasonably priced parts were available, the shipping cost would probably deter most consumers from attempting repair on a $20 keyboard. Mechanical keyboards are also inherently quite modular. Keyboard enthusiasts have shaped a market where there are endless customization options. DIY builds are commonplace, and so are replacement parts.

To further illustrate the differences between mechanical and membrane keyboards, teardowns of each will be provided. The mechanical keyboard examined here is a Glorious GMMK Pro. Glorious claims the GMMK keyboard is “the world’s first fully modular mechanical keyboard” [37]. From the “Build” tab on their website, consumers can select their desired layout, housing, switches, and keycaps. A teardown of the GMMK Pro is shown in Figure 10.
The GMMK Pro was straightforward to disassemble. To fully separate all the components as shown in Figure 10, there were a total of 30 Phillips screws. There were 8 screws connecting the top covering to the base. The volume knob also needed to be removed before lifting off the top covering. The power cable separated easily from its connector on the PCBA. After this, there were 20 screws on the back of the PCBA holding it to the baseplate (with a layer of foam and two plastic spacers in between). Two screws were mounted on the baseplate (where the switches are mounted) and connected to the PCBA with threaded inserts. To remove these last two screws, a few keycaps had to be removed. The most difficult part was reattaching these two screws during reassembly (I used masking tape to secure the threaded inserts in place on the back of the PCB.
before attaching the screws). Of course, the switches and keycaps can be easily swapped out without doing any of the disassembly mentioned above.

The membrane keyboard chosen for examination is the HP Model KU-1469—which is the same keyboard selected for the product design case study in Chapter 4. A teardown of the KU-1469 is shown in Figure 11.

![Figure 11. HP KU-1429 Membrane Keyboard Teardown.](image)

This membrane keyboard was fairly straightforward to disassemble. It had a total of 19 Phillips screws. 14 of these were used to connect the top and bottom housing. However, four of these screws were hidden beneath adhesive—two of them below adhesive feet and two of them behind the product label. Inside the keyboard, five larger screws secured the PCBA and baseplate. After removing the screws, the plastic film layers and rubber dome layer could be easily removed. To reassemble the layers, they can be realigned using the plastic extrudes on the housing. Membrane keyboards are the focus for this work because they provide a significant opportunity to reduce electronic waste in one of the most disposable products on the market.
2.3 TOPIC MODELING BACKGROUND

2.3.1 NATURAL LANGUAGE PROCESSING OVERVIEW

Natural language processing (NLP) broadly refers to the application of machine learning models for human language. Using linguistic statistics and numerical language models, machine learning models can extrapolate from their training to decipher and generate text [38]. In practice, NLP is used for many different purposes. A few examples are media apps that give automatic recommendations for books and movies, email platforms with automatic spam detection, and voice assistants like Siri and Alexa. In recent months, NLP for generative text (often called “generative AI”) has surged in popularity with the explosion of ChatGPT and many competitor chatbots and assistants.

2.3.2 TOPIC MODELING OVERVIEW

This research uses topic modeling, which is a specific natural language processing technique. Topic modeling is used for discovering semantic (meaningful) topics within a collection of documents. Topic modeling can be used for summarization, classification, and retrieval of documents based on their textual content. It has proven to be effective in extracting insights from text data and has been implemented to support the early stages of product design [39], [40], [41], [42]. While several approaches exist for topic modeling, this research focuses on two methods: Non-negative Matrix Factorization (NMF) and BERTopic. These methods are chosen for their efficacy in discovering semantic topics within short and unstructured text data, such as the Amazon product reviews used in this work [43].

2.3.3 DIFFERENT TOPIC MODELING METHODS

The two approaches for topic modeling explored in this research are Non-Negative Matrix Factorization (NMF) and BERTopic. NMF is notable for its useful applications in text mining.
NMF is a vector space method that makes use of non-negativity constraints to organize text data into meaningful categories [46]. In the NMF approach, a corpus of documents (here, product reviews) is represented as a word-by-document matrix that represents the frequency of words (rows) occurring in documents (columns). The matrix is factorized into 1) word-by-topic matrix, whose ith topic column is represented by a weighted distribution of words, and 2) topic-by-document matrix, whose jth document column is represented by a weighted distribution of topics. This allows for representations of documents as linear combinations of topics and topics as linear combinations of words, where all coefficients must be non-negative [47].

BERTopic is a topic modeling methodology developed by Maarten Grootendorst in 2020 [48]. In the BERTopic approach, the BERT transformer-based model is used to convert documents into vector representations called document embeddings. The dimensionality of the embeddings is reduced to form clusters of semantically similar documents where each cluster represents a topic. To extract the topic representation from each of these clusters, a class-based TF-IDF method is used [49]. BERTopic is novel in comparison to standard topic models (such as NMF) because it categorizes text without disregarding the “semantic relationships among words” [49]. Where NMF builds topics based on a collection of words, BERTopic also takes into consideration the context in which the words are used. In this research, both NMF and BERTopic are applied to text from repairability-related Amazon product reviews to learn more about the specific keyboard issues most often discussed.

2.4 LITERATURE REVIEW

2.4.1 PRODUCT REPAIRABILITY RESEARCH

There have been recent research efforts aimed at promoting product repairability. Repairability is closely linked to disassembly, as the ease of disassembling a product directly influences how easily it can be repaired. For example, with the goal of advancing design for repairability of
mechatronic products, [50] and [51] use a case study of electro-mechanical ovens to introduce and apply an eco-design framework. In [50], researchers propose a methodology for establishing eco-design rules based on factors such as disassembly complexity, disassembly time, tooling, fasteners, and connectors.

Efforts to achieve a circular economy (where resources are reused instead of discarded) are closely linked to device repair. The circular economy goal is not only dependent on device repairability, but also on consumer repair practices. Researchers have investigated both consumer behavior and product repair experiences. For instance, [52] integrated consumer repair decisions and the deterioration process of components to evaluate the lifecycle of consumer electronics (e.g., laptops). Additionally, [53] explored consumer repair motivation and barriers through workshops, resulting in a repair motivation and barriers model that includes technical, emotional, and value aspects of repair.

One strategy to support product repairability is the identification of product failure modes. For example, [54] and [55] use Support Vector Machine (SVM) to forecast the failure modes of medical devices from repair and maintenance records. This would aid in determining appropriate repair strategies. While this approach also focuses on the identification of product failure modes, the approach presented in this thesis leverages customer feedback, which reflects the product experiences of a range of users.

2.4.2 RELATED WORK

Previous work from Saidani et al. studied whether sustainable design insights could be obtained from Amazon product reviews using manual methods. The researchers also provided insight on machine learning approaches [56], [57]. Their manual method had three steps: 1) read customer reviews of Amazon Climate Pledge Friendly and standard products (e.g., cables, printers, laptops) and identify mentions of sustainability, 2) link sustainability mentions to specific product features
and classify reviews by how directly they mention sustainability, and 3) interpret review content to obtain sustainable design leads. The results showed both general design insights and those specific to the cables, printers, and laptops examined. General design insights indicated that reviewers did discuss aspects of sustainable design and were most likely to mention sustainable aspects that directly benefited them (such as component durability). Furthermore, the researchers concluded that the reviews could be interpreted to obtain leads for product designers, and they recommended future work in automating such a process [56].

From their paper on machine learning approaches [57], Saidani et al. outlined a framework for automating the process of obtaining sustainable design insights from customer reviews. They described a three-step process: 1) make use of natural language processing (NLP) to construct a machine learning pipeline for automation, 2) evaluate and improve the models as needed, and 3) scale and deploy the design tool, ideally through an accessible web platform [57]. The work in the present paper falls under the first objective with a narrowed focus on design for repairability, which is a subset of sustainable design.

Additionally, previous work has combined life cycle assessment (LCA) results with information from sustainability-related online reviews to obtain insights for sustainable design. In their paper [58], Saidani et al. discuss the advantage of using user feedback to provide precise design insights to complement more generic LCA findings. While LCA provides numerous uses for quantifying environmental impact, leveraging online customer feedback could give designers sources of inspiration to address specific sustainability concerns [58].

Other NLP work using Amazon reviews includes efforts to understand latent customer needs, which are needs “implied in the semantics of use cases” [40]. By contrast, explicit needs (those mentioned directly) are much easier for text mining approaches to handle. In their work to unveil latent customer needs, Zhou et al. used sentiment analysis as a first step in differentiating types of
customer use cases. They used sentiment analysis to evaluate whether users had positive or negative responses to specific product features [40]. Sentiment analysis can be applied similarly to sustainable design efforts because capturing more nuanced customer needs yields more comprehensive feedback. In the present research, sentiment analysis was used to separate product problems from praise.

Previous research has also applied topic modeling to failure mode identification of complex engineering systems, which is similar to using topic modeling to evaluate repairable design. In their work, Andrade et al. discussed applying latent Dirichlet allocation (LDA) topic modeling to NASA’s Lessons Learned Information System. Their research goal was to determine if narratives surrounding engineering failures could be useful for failure mode prevention. Their approach extracted the cause, failure, and recommendation from each entry, resulting in a failure taxonomy for future reference [59]. Similar ideas could be applied to organizing the repairability design insights obtained from Amazon product reviews. The creation of a repair-need taxonomy for a variety of consumer electronics could give product designers access to specific repair-relevant information with little required effort. With the addition of device-specific insights such as those presented in this research, product designers would be well equipped to design devices that last, helping to reduce their environmental impact.
3. TOPIC MODELING

3.1 RESEARCH APPROACH

To examine if customer feedback from Amazon reviews can help designers obtain repairability-related design insights, a two-part approach was used. This approach included 1) evaluating a comprehensive range of repairability-related issues across a category of devices and 2) comparing specific models within that category. Standalone computer keyboards were selected as a case study to examine the efficacy of this approach. This methodology is split into three steps: 1) obtain repairability-related Amazon reviews for keyboards, 2) perform topic modeling using NMF and BERTopic to discover general trends, and 3) compare failure modes for three specific keyboards. Each step is explained in detail in the following sections.

3.2 METHODOLOGY

3.2.1 EXTRACTING REPAIRABILITY-RELATED TEXT DATA

This research used Amazon product reviews for 10 standalone computer keyboards found under the search term "office keyboard". Keyboards were chosen that had a large number of reviews in order to capture a diverse range of customer experiences. Since reviews typically contain a mix of opinions (e.g., likes and dislikes), they were parsed into sentences for the analysis presented in the subsequent sections. To capture repairability-related reviews, a filtering process was needed to distinguish repair-relevant review content from other customer comments. A repairability keyword list was developed for this purpose.

Developing the repairability keyword list involved an iterative process of brainstorming and refining. Initially, 300+ keywords were generated by reviewing iFixit articles and manually creating a list of words [6], [13]. Additional brainstorming to add to the list involved creating keywords for various categories related to repairability, such as tools, action verbs, and
components related to repair. Subsequently, the keyword list was refined by evaluating its performance in filtering repairability-related product reviews. This evaluation compared the automatically filtered results to manually sorted results. 2000 randomly selected review sentences were sorted manually by a primary coder based on whether they were related to repairability using the following criterion:

Reviews are considered repairability-related if they include content about a keyboard failure mode or attempted repair; this includes feedback about keyboard component malfunctions and physical damage but not feedback on undesirable design features.

For example, a repairability-related keyboard review is “keyboard needs to be unplugged and plugged back into usb port daily in order to function” because it describes a malfunction. On the other hand, an example of a non-repairability review is “I am very surprised to find it has no feet in the back to provide a proper tilt for typing” because the review is commenting on a perceived design flaw. Interrater reliability analysis was conducted by having a second coder independently sort 15% of the data with the provided criterion. The Cohen’s Kappa was run to determine that there was a sufficient agreement between the two coders’ decisions, $κ=0.760$. After achieving this Cohen’s Kappa, the keyword list was refined iteratively by examining how slight changes affected what was flagged as repairability-related. Once 85% of the 2000 test sentences were correctly flagged, the keyword list was accepted. This resulted in a list of 42 repairability keywords. Examples from the list include “disconnect”, “screw”, “troubleshoot”, and “unresponsive.” The complete list of keywords is given in Appendix A.

3.2.2 TOPIC MODELING WITH NMF AND BERTOPIC

To prepare the filtered sentences for topic modeling, a few additional steps were needed. First, sentiment analysis was performed to categorize sentences as either being positive or negative. Only the negative sentences were used for topic modeling to maintain focus on keyboard failure
modes. For NMF, the filtered sentences were preprocessed using NLP modules in Python. This included removing stopwords and tokenization. The words “work” and “keyboard” were added to the stopwords list to reduce noise in the data due to their frequent usage in the reviews. This preprocessing was not needed for BERTopic because it uses the transformer model BERT to effectively process the original text data.

Topic modeling was performed using both NMF and BERTopic on the collection of repairability-related sentences. Review sentences from all 10 keyboards were considered to examine failure mode trends across devices and provide sufficient text data for topic modeling.

### 3.2.3 EVALUATING FAILURE MODES FOR SPECIFIC DEVICES

After topic modeling was performed to analyze general trends, three keyboards were studied individually to determine 1) if the sentence filtering method could be used to learn about the repairability of individual devices and 2) if this method could be used to compare device repairability. Three keyboards of a similar price range were selected from the original group of 10 keyboards. Table 1 gives further details on the three keyboards selected for comparison.

<table>
<thead>
<tr>
<th></th>
<th>Keyboard 1: Logitech K120 Wired Keyboard</th>
<th>Keyboard 2: Arteck Wireless Keyboard</th>
<th>Keyboard 3: Amazon Basics Wired Keyboard</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photo</strong></td>
<td><img src="image1" alt="Keyboard 1: Logitech K120 Wired Keyboard" /></td>
<td><img src="image2" alt="Keyboard 2: Arteck Wireless Keyboard" /></td>
<td><img src="image3" alt="Keyboard 3: Amazon Basics Wired Keyboard" /></td>
</tr>
<tr>
<td><strong>Manufacturer</strong></td>
<td>Logitech</td>
<td>Arteck</td>
<td>Amazon Basics</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Wired</td>
<td>Wireless</td>
<td>Wired</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>~ $20</td>
<td>~ $40</td>
<td>~ $14</td>
</tr>
<tr>
<td><strong>ASIN</strong> (Amazon Standard Identification Number)</td>
<td>B003ELVLKU</td>
<td>B07D34L57F</td>
<td>B07WJ5D3H4</td>
</tr>
</tbody>
</table>

Table 1. Keyboards Selected for Comparison.
To compare these models, the keyword list was used to extract repairability-related sentences from the collection of reviews for each keyboard. These three keyboards had 217, 219, and 162 repairability-related sentences used for comparison, respectively. The extracted sentences were then manually read and synthesized to determine common failure modes for each device. Note that topic modeling was not conducted for comparison analysis due to the limited number of reviews available for each individual device. Results are presented in the following section.

3.3 RESULTS AND DISCUSSION

3.3.1 TOPIC MODELING RESULTS FOR 10 KEYBOARDS

For each of the 10 keyboards, 100 reviews were scraped for each star rating (i.e., 1~5-star ratings), resulting in 500 reviews for each product. This resulted in a total of 34,925 sentences. Using the keyword list, 1,886 repairability-related sentences were extracted.

The results for both the NMF and BERTopic approaches are given in this section, as well as a comparison between them. For the NMF approach, a coherence score methodology was used to determine the best number of topics based on the input data. This resulted in 75 topics. For BERTopic, 35 topics were identified, where the number of topics was selected automatically. For both NMF and BERTopic, many of the identified topics indicate keyboard failure modes and repair needs. Selected NMF and BERTopic results that represent failure modes are given in Table 2. Most topics are represented by five words determined by the topic modeling methods (a few topics only have three or four words depending on the topic modeling result).
Table 2. Failure Mode Representative Topics from NMF and BERTopic.

<table>
<thead>
<tr>
<th>Failure Modes</th>
<th>NMF</th>
<th>BERTopic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keys sticking</td>
<td>Topic: “key, stick, annoy, issue, already”</td>
<td>Topic: “sticking stick, keys, sticky, random”</td>
</tr>
<tr>
<td>Letters wearing off the keys</td>
<td>Example: “the caps lock and shift on the left kept sticking”</td>
<td>Example: “keys are sticking”</td>
</tr>
<tr>
<td>Wobbly keyboard base</td>
<td>Topic: “letter, wear, key, easily, miss”</td>
<td>Topic: “wear, letters, wearing, keys, letter”</td>
</tr>
<tr>
<td></td>
<td>Example: “eventually the white on the keys wears off, but only after a couple of years”</td>
<td>Example: “letters are wearing off of the keys”</td>
</tr>
<tr>
<td></td>
<td>Topic: “wobble, flat, desk, adjust, sit”</td>
<td>Topic: “wobbles, wobbly, desk, wobble”</td>
</tr>
<tr>
<td></td>
<td>Example: “the one I received is wobbly and does not sit evenly”</td>
<td>Example: “it doesn’t lay flat and wobbles while I type”</td>
</tr>
<tr>
<td>Keyboard legs breaking</td>
<td>Topic: “leg, break, flimsy, snap, plastic”</td>
<td>Topic: “legs, feel, break, angle, kicksstands”</td>
</tr>
<tr>
<td></td>
<td>Example: “even though they say it is built to last, one of the keyboards legs broke off within about a month of use”</td>
<td>Example: “the legs break easily”</td>
</tr>
<tr>
<td>Keyboard disconnecting</td>
<td>Topic: “disconnect, random, frequent, wire, time”</td>
<td>Topic: “disconnects, connectivity, disconnect”</td>
</tr>
<tr>
<td></td>
<td>Example: “do not buy - these sub keyboards disconnect randomly after a few minutes”</td>
<td>Example: “now it is constantly disconnecting”</td>
</tr>
<tr>
<td>Bluetooth disconnecting</td>
<td>Topic: “connect, device, bluetooth, disconnect, issue”</td>
<td>Topic: “bluetooth, disconnects, paired, device, pair”</td>
</tr>
<tr>
<td></td>
<td>Example: “I have to go to bluetooth on the mac to re-pair and reconnect, which takes a couple of minutes”</td>
<td>Example: “the bluetooth disconnects constantly and takes a while to reconnect”</td>
</tr>
<tr>
<td>Keyboard lagging</td>
<td>Topic: “lag, long, frequent, input, click”</td>
<td>Topic: “unresponsive, lagging, issues”</td>
</tr>
<tr>
<td></td>
<td>Example: “there was also a lag in response time which made using the arrows and navigation buttons evaporating”</td>
<td>Example: “mostly no issues for first five or so months, but now totally unresponsive”</td>
</tr>
<tr>
<td>Need to unplug/re-plug</td>
<td>Topic: “unplug, plug, sub, constant, need”</td>
<td>Topic: “unplug, unplugged, plug, charging, charge”</td>
</tr>
<tr>
<td></td>
<td>Example: “you have to unplug/plug-in throughout the day”</td>
<td>Example: “at first, I could just unplug the sub and plug it back in, now that only works some of the time”</td>
</tr>
<tr>
<td>Missing letters/typing errors</td>
<td>Topic: “type, letter, error, keystroke, miss”</td>
<td>Topic: “missing, typing, type, letters, errors”</td>
</tr>
<tr>
<td></td>
<td>Example: “the keys are extremely unresponsive so a lot of words will be missing letters and you have to go back and fix it”</td>
<td>Example: “I’m an experienced typist, but the sheer number of times I’ve had to stop to correct extra or missing letters is slowing my typing to a crawl”</td>
</tr>
</tbody>
</table>

As shown, both NMF and BERTopic identified relevant repairability information and failure modes from the Amazon product reviews. For instance, both approaches identified problems with keys sticking, Bluetooth disconnecting, keyboard legs breaking, and unstable keyboard bases. This continuity gives confidence to the notion that topic modeling of Amazon product reviews can identify failure modes and provide leads for designers. For example, feedback about keyboard legs snapping off might inspire designers to improve keyboard leg durability and provide or sell replacement keyboard legs.

In addition to meaningful topics such as those given in Table 2, results from both NMF and BERTopic include topic redundancy and noise in the data. For NMF, examples of topics that show noise in the data include “year, use, break, wear, fix, sever, suppose, cable, decent, pretty,” “problem, fix, doesn’t, manufacture, search, appear, hope, care, amazon,” and “day, time,
multiple, every, return, final, got, window.” Examples of duplicate topics from NMF include “constant, disconnect, bluetooth, wifi, unfortunate, require” and “connect, device, bluetooth, disconnect, issue, another, wireless, lose.” Both topics are about the keyboard’s Bluetooth disconnecting from the paired computer. While BERTopic generated fewer topics than NMF, there are still redundant topics and topics that do not represent failure modes. Examples of redundant topics include “bar, space, spacebar, sticks, sticking” and “bar, space, spacebar, started, sticking.” Both of these topics are about the spacebar sticking. Examples of topics that show noise in the data are “fix, troubleshooting, tried, fixed, problem,” “key, expensive, board, need, used,” and “stars, star, fast, minus, purple.”

While repairability-related design insights can be obtained from both approaches, the approaches differed in performance. BERTopic resulted in more consolidated topics, with fewer duplicates and fewer topics without repair substance. On the other hand, NMF resulted in a greater number of incoherent topics, which matches previous performance with short text data [43].

The overall conclusion from this work is that repairability-related design insights can be derived from customer feedback. This methodology can be used by designers to improve the repairability, and thus sustainability, of their products. Additionally, there is room for future work to refine the application of topic modeling for this purpose.

### 3.3.2 COMPARISON RESULT FOR 3 SELECTED KEYBOARDS

From manually evaluating different keyboards based on repairability-related sentences, keyboard-specific failure modes of three different devices were identified. Table 1 gives an overview of the three keyboards chosen for comparison. Results for the failure mode comparison, including examples from customer reviews, are given in Table 3.
These results qualitatively show the repairability-related insights that can be obtained from customer feedback. While this evaluation does not present information on the magnitude of these issues, it is still useful to know the failure modes present for each device. Many of the same failure modes were present across devices and match the trends uncovered from topic modeling. For instance, all three keyboards had issues with sticky keys, and two of them had issues disconnecting from the paired computer. Unique issues were also picked up through this process, including letters wearing off keyboard #1 and keyboard #3 wobbling on the desk. These keyboard-specific findings indicate the potential for future work that uses customer feedback to compare the repairability of various electronic devices.

### 3.3.3 APPLICATIONS

There are two main applications for repairability-related insights derived from customer feedback. First, as mentioned, this methodology could be used as a design tool. In early product design and development stages, product designers could employ this approach to learn about common repair concerns for devices already on the market. In doing this, they would learn aspects of their product where durability should be a priority, which components are repair-

<table>
<thead>
<tr>
<th>Failure Modes</th>
<th>Keyboard 1: Logitech Wired Keyboard</th>
<th>Keyboard 2: Arteck Wireless Keyboard</th>
<th>Keyboard 3: Amazon Basics Wired Keyboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keys sticking</td>
<td>“the keyboards are nice at first, then the keys get sticky and the letters rub off”</td>
<td>“after cleaning the keyboard there were a few that were sticking”</td>
<td>“after about a year of use, the spacebar started to stick”</td>
</tr>
<tr>
<td>Letters wearing off the keys</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Wobbly keyboard base</td>
<td>X</td>
<td>X</td>
<td>“wobbles when I type and can’t be adjusted”</td>
</tr>
<tr>
<td>Keyboard legs breaking</td>
<td>“till legs break easily”</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Keyboard disconnecting</td>
<td>X</td>
<td>“constantly disconnects and need to charge the battery multiple times a day to even keep it functional”</td>
<td>X</td>
</tr>
<tr>
<td>Bluetooth disconnecting</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Keyboard lugging</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Need to unplug/re-plug</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Missing letters/typing errors</td>
<td>X</td>
<td>“I thought at first it was just my typing but after using it for a few days and letting the battery get lower I noticed that if I let it get really low it was missing 1/2 the keys I pressed and I’d really have to push down on the buttons to get them to respond”</td>
<td>X</td>
</tr>
</tbody>
</table>
critical (to ensure easy-access and modularity), and which components to make available as replacement parts. Product designers could also use this approach to make improvements to their own existing products that have already received customer reviews.

The second potential application is for consumers. Repair-conscious consumers have the power to drive change by supporting the companies trying to change the disposable electronics paradigm. For consumers selecting a product with repairability in mind, a way to compare the repairability of different products based on customer feedback would be useful. While expert repairability scores (such as those from iFixit) reflect in-depth teardowns and design for repairability analysis, they do not necessarily predict the failure modes of a device based on real, long-term usage. Additionally, expert repairability scores are not available for all devices. For a consumer-facing platform, the methodology proposed here and future work automating a repairability comparison tool would likely need a user-friendly interface and web-accessibility.

3.4 LIMITATIONS AND FUTURE WORK

There are several limitations to this research and areas that warrant continued research and development. The first limitation is the performance of the keyword list for repairability-related sentence filtering. Additional methods for list refinement should be explored and tested with the goal of achieving a sorting accuracy above 85%. A second limitation is the quality of the topic modeling results. While still largely useful for deriving repairability-related design leads, the topics were sometimes unclear and unconsolidated. Improvements to the topic modeling approach would be useful for future development of this work as a design tool.

Other next steps in this research include applying it to other products of varying complexity and mechanical functionality (i.e., laptops or washing machines). It may also be useful to explore classifying failure modes as electrical or mechanical failures. Additionally, text data from online repair forums or expert reviews and performance tests could be used for topic modeling. This
would allow comparison between the repairability design insights from these sources and the insights derived from customer feedback.

To ensure this process can be easily implemented, it would be useful to transform the device repairability comparison from a manual to an automatic process and make it more quantitative. There is also an opportunity to transform the topic modeling approach into a more user-accessible design tool and/or consumer reference.

Additionally, integrating qualitative repairability design leads with quantitative sustainable design metrics early in the product design process could magnify the environmental benefit. For instance, repairability design leads could be used with circular economy indicators to quantify the product circularity benefit from enhanced repairability [60]. Repairability design leads could also be coupled with other quantitative and qualitative sustainable design methods, such as the approach in [61] that focuses on improving end-of-use product value recovery.
4. PRODUCT DESIGN CASE STUDY

4.1 CASE STUDY APPROACH

This product design case study has two purposes. The first is to show how the design insights obtained through topic modeling can be applied in repairable product design. The second is to demonstrate design for electronic component reuse. This chapter will present an accelerated example of product development for a repairable, standalone computer keyboard. In addition to addressing common keyboard failure modes from the topic modeling results, this design will make use of electronic components from existing waste keyboards. This allows waste keyboards to be reused through a “piggybacking” design approach, where new components are added (and others discarded) to extend the lifespan of the electronics.

If a membrane keyboard is unwanted due to mechanical failure modes (such as missing or cracked keycaps) or personal preferences (such as aesthetics or a distaste for mushy keys), its electronics can be reused for this keyboard transformation. Instead of trashing old electronics or attempting to separate metals and plastics in a difficult recycling process, the most environmentally conscious thing to do with working electronic components like PCBAs is reuse them. A possible vision that puts this into practice would be a computer keyboard company that collects waste keyboards, harvests their electronics, and transforms them into new keyboards to sell. Of course, this would also be an ideal circular economy model for modular smartphones, laptops, headphones, etc.

This same idea could also manifest as a company that sells DIY build kits to consumers, where individuals receive all the necessary parts to build their own keyboard (or phone or laptop!) from waste electronics. A second-best alternative to a company that supplies build kits would be a website with all the necessary instructions for interested individuals to pursue keyboard transformation themselves. This would include online build instructions with a list of components.
to purchase and downloadable part files to 3D print. This last idea is the ultimate end goal for this thesis work, once the design has been refined (as discussed in section 4.8 Upcoming Design Refinements and Chapter 5 Sharing Results).

The target consumer for a company that supplies an electronic transformation build kit would be, hopefully, anyone. The goal for this theoretical company would be to supply all the tools, instructions, and components to make it as easy as possible for anyone to feel excited and confident about completing their DIY build. The only prerequisite for working on this project would be a willingness to expend the time and effort to complete it.

It would be best to avoid marketing this type of kit as only for those who are tinkerers, electronic hobbyists, engineers, etc. because this may turn away capable and excited, environmentally conscious consumers who are waiting to be introduced to electronics repair. This is succinctly described by Manuel Haeussermann from iFixit, who writes “At iFixit, we champion the idea that with the right tools, parts, and guidance, anyone can roll up their sleeves and mend their tech treasures. This isn’t just about fixing what’s broken; it’s about reclaiming a sense of agency over the devices we own” [62]. Of course, not all consumers may want to expend the time and effort required to transform their electronic waste into a new product, so the company could also sell pre-built models in addition to DIY kits (similar to the current product scheme offered by Framework).

For an instructional website with accessible files, the barrier to entry would inevitably be higher. Since consumers would have to acquire the parts on their own (some of which require 3D printing), it may take significantly more time and effort to complete the DIY build than it would with a provided kit. The instructions and terminology on the website should still encourage anyone to attempt the project (no skills required), but it should be clear that it is a somewhat involved project. Clear instructions for how to complete the build and what components to
acquire are a must-have. Additionally, for individuals without access to 3D printers, the online instructions could point to companies that 3D print files and ship them to customers.

As of the completion of this thesis, the keyboard design requires additional refinements and development time before it is ready to be published online and built by others. However, a website has already been created for this purpose and will have additional information coming soon. This is discussed in Chapter 5 Sharing Results.

4.2 FAILURE MODES AND COMPLAINTS TO ADDRESS

Since the goal is to transform waste keyboards into usable and desirable products, the repairable keyboard design should address the reasons the keyboard was deemed waste. To achieve this, the topic modeling findings from the NLP research can be used. Table 4 gives the topic modeling results for mechanical failure modes, as well as possible causes and potential solutions.
Table 4. Failure Modes from Topic Modeling Results.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Possible Causes</th>
<th>Potential Design Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keys sticking</td>
<td>Dust and debris impairing key travel. Rubber dome gets stuck in the down position. Too much friction in plastic sliding mechanism. Rubber dome is not pressed down in the center.</td>
<td>Easily removable keycaps to allow for cleaning. Addition of spring mechanism to reduce likelihood that rubber dome will be stuck in compressed state. Design for adequate sliding fits between components to reduce friction. Careful alignment to ensure force on rubber dome acts through the center.</td>
</tr>
<tr>
<td>Letters wearing off the keys</td>
<td>Application of letters does not hold up to prolonged use.</td>
<td>Select a more durable adhesive sticker/coating for the letters. Design letters as a different color plastic that press fit into the keycaps. Design letters as cutouts in the keycaps with lights beneath. Use heavy duty stickers for the letters and provide users with ample replacements.</td>
</tr>
<tr>
<td>Wobbly keyboard base</td>
<td>Limited structural rigidity due to thin plastic. Few contact points with the supporting surface. Uneven or unstable keyboard legs, etc.</td>
<td>Design the base to have full contact with the work surface and be of sufficient thickness. If keyboard legs are included, ensure the feet have enough contact area with the supporting surface. Also ensure the keyboard legs are the same length and locating features are built into the design to make sure the legs are aligned.</td>
</tr>
<tr>
<td>Keyboard legs breaking</td>
<td>Legs are blocked from rotating a full 360 degrees, so if they are over extended, they easily snap (shear or bending failure). Legs are made of thin plastic. Leg attachment to keyboard has rigid geometry that results in stress concentrations.</td>
<td>If keyboard legs are included, ensure they are thick enough to withstand typical bending and shear loads. Improve the leg rotation mechanism so they lock into place and cannot be overextended. Provide customers with replacement legs.</td>
</tr>
<tr>
<td>Missing letters/typing errors</td>
<td>Feedback from key press is not tactile enough (user cannot immediately tell if a key is registered). Keycap actuation requires too much force. Keyboard cannot register multiple key presses at the same time. Rubber dome is not compressed fully or is stuck down. Rubber dome is not actuated in its center.</td>
<td>Improve keycap tactility by adding a spring mechanism similar to how tactile mechanical keyboard switches work. Ensure the component between the keycap and the rubber dome has sufficient contact area with the rubber dome to evenly transmit the load.</td>
</tr>
</tbody>
</table>
Additional complaints and reasons for keyboard disposal are listed in Table 5 with design solutions to address them. These complaints were identified during the manual review of repairability-related sentences done to assess keyword list performance. These complaints are useful because they could be common reasons that individuals choose to discard their keyboard and replace it. For future work applying this methodology to other products, using a topic modeling approach to identify complaints, in addition to failure modes, could be useful.

Table 5. Common Keyboard Complaints.

<table>
<thead>
<tr>
<th>Complaint</th>
<th>Possible Cause</th>
<th>Potential Design Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mushy keys</td>
<td>Compressing directly on the rubber dome is innately “mushy.”</td>
<td>Modify the mechanism that interfaces the keycap press with the rubber dome to decrease “mushiness.”</td>
</tr>
<tr>
<td>Lost keycaps</td>
<td>Keycaps don’t stay securely connected to keyboard housing. In school settings, it may be fairly common for children to remove keycaps.</td>
<td>Ensure keycaps are securely connected to housing but also easy to remove if desired. Replacement keycaps should be easily accessible so an entire keyboard does not need to be discarded if one keycap goes missing.</td>
</tr>
<tr>
<td>Unpleasing aesthetic</td>
<td>Consumers differ in aesthetic values and their preferences may change over time. New product marketing is always trying to catch the consumers’ eyes, so old devices might not look as flashy or be as pleasing to use.</td>
<td>Housing design should aim to be timeless and well-crafted. It should also be replaceable, just like the rest of the keyboard, in case it gets damaged.</td>
</tr>
<tr>
<td>Too light (doesn’t feel sturdy)</td>
<td>Rubber dome membrane keyboards typically have all plastic encasings without added weights.</td>
<td>Additional metal components or weights could be added to improve perceived sturdiness, though this might not be worth the added complexity, cost, and resources.</td>
</tr>
</tbody>
</table>

A complete design that addresses these failure modes and complaints will be outlined in the coming sections.
### 4.3 DESIGN OBJECTIVE AND REQUIREMENTS

The primary design objective is to make a keyboard that addresses common failure modes to prioritize repairability, reuse waste electronic components, use off-the-shelf (OTS) parts as much as possible, and still function. Table 6 further outlines the keyboard requirements.

Table 6. Keyboard Requirements.

<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
<th>Description</th>
<th>Verification Method</th>
<th>Description of Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Functionality</td>
<td>The keyboard works comparably to other functioning membrane or mechanical keyboards—an average keycap press results in the corresponding letter appearing on screen.</td>
<td>Phase 1: Keyboard Functionality Test.</td>
<td>Phase 1: use a keyboard functionality test to press each key and ensure the corresponding character is registered.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Phase 2: User Functionality Test and Feedback.</td>
<td>Phase 2: have at least three users trial the keyboard for typing and complete a survey rating the functionality and giving qualitative feedback.</td>
</tr>
<tr>
<td>2</td>
<td>Secure Component Alignment</td>
<td>Components do not move relative to each other in the keyboard housing when the keyboard is moved or jostled.</td>
<td>Handheld Shake Test</td>
<td>Perform a light shake test while holding the keyboard and inspect component alignment before and after.</td>
</tr>
<tr>
<td>3</td>
<td>Repairable After Typical Fall</td>
<td>After a fall from a typical desk surface, the keyboard can be repaired.</td>
<td>Desktop Drop Test</td>
<td>Knock the keyboard off a desk and determine if it can be easily repaired with replacement components from the original build materials. Perform a keyboard functionality test after</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Waterproof to Typical Spill</td>
<td>After liquid from an average drinking cup spills on the keyboard, there is no water ingress through the PCBA enclosure and the keyboard still functions.</td>
<td>Liquid Spill Test</td>
<td>Knock over a cup of water next to the keyboard, and use water ingress detection labels to determine if water has entered the PCBA enclosure. Perform a keyboard functionality test after the spill.</td>
</tr>
<tr>
<td>5</td>
<td>Repairable Design</td>
<td>Keyboard should follow the design for repairability guidelines outlined in section 2.1.1.</td>
<td>Review Repairable Design Guidelines with Final Design</td>
<td>With the final design, go through the Repairable Design Guidelines from section 2.1.1 and explain how each guideline is addressed or why it does not apply.</td>
</tr>
<tr>
<td>6</td>
<td>E-Waste Reuse</td>
<td>Keyboard electronic components are reused from a discarded rubber dome membrane keyboard.</td>
<td>Review Final Design</td>
<td>Review the final design to ensure all electronic components are reused.</td>
</tr>
<tr>
<td>7</td>
<td>Off-the-shelf Component Usage</td>
<td>Additional keyboard components (not those reused) are OTS components whenever possible.</td>
<td>Review Final Design</td>
<td>Review the final design to ensure OTS components are used whenever possible.</td>
</tr>
<tr>
<td>8</td>
<td>Addresses Common Mechanical Failure Modes</td>
<td>Keyboard design addresses the failure modes identified from topic modeling results (see section 4.2).</td>
<td>Review Final Design</td>
<td>Review the final design to ensure selected mechanical failure modes from section 4.2 are addressed.</td>
</tr>
<tr>
<td>9</td>
<td>Effective Keyboard Build Instructions</td>
<td>The build instructions are sufficient to guide a non-engineering individual through the build process with user satisfaction.</td>
<td>User Build Test and Feedback</td>
<td>Have at least two non-engineering users complete the build process using the instructional materials and provide feedback.</td>
</tr>
</tbody>
</table>
These requirements are relevant to the final design and should be verified before the final design is made available online. However, many of these requirements and tests are beyond the scope of this thesis work. Addressing all design requirements and completing verification testing is left to the future work for this project.

4.4 SELECTED KEYBOARD FOR E-WASTE REUSE

This design will reuse components from waste rubber dome membrane keyboards. Rubber dome membrane keyboards were selected because they are a common, inexpensive keyboard that is seldom repaired in the United States. At a low price point (around $10-$50), the average consumer does not hesitate to discard a membrane keyboard and likely does not consider repair. Manufacturers have no reason to offer replacement parts, so membrane keyboards (and the electronics inside of them) are often treated as consumables. Additionally, these keyboards are often chosen for purchase in bulk for workplaces, schools, universities, etc. This means they flow steadily through the consumer goods economy and are fairly plentiful electronic waste to acquire and reuse.

For this research, 30 waste keyboards were received (some donated from a friend’s mom who works in a middle school and some from Ebay). The keyboards from the middle school were mostly those discarded for being nonfunctional for one reason or another (missing keycaps, broken housing, stuck keys, misbehaving electronics, etc.). The keyboards from Ebay have unknown backstories, but they were sold in bulk as $50 for a collection of 15 (along with some computer mice) and stated to be functional. Of the total keyboard inventory for this project, the most common model was the HP KU-1469, which is a thin, membrane keyboard (see Figure 12).
Figure 12. HP Model KU-1469 Keyboard.

This model was selected for this design because it was important to have enough devices of the same model available for prototyping and testing. Additionally, this model was very similar to other HP models in the keyboard inventory, such as SK-2120 and KBAR211. The KU-1469 keyboard is a 100% layout wired keyboard that uses a rubber dome layer. A teardown of one of the KU-1469 keyboards is shown in Figure 13.

Figure 13. HP Model KU-1469 Teardown.

The components of this keyboard are described in Table 7.
Table 7. HP Model KU-1469 Components.

<table>
<thead>
<tr>
<th>Component Number</th>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top Housing</td>
<td>Protect internal components and house keycaps.</td>
</tr>
<tr>
<td>2</td>
<td>Bottom Housing</td>
<td>Protect, align, and stabilize internal components.</td>
</tr>
<tr>
<td>3</td>
<td>Keyboard Legs</td>
<td>Provide keyboard angle for easier typing and improved ergonomics.</td>
</tr>
<tr>
<td>4</td>
<td>Keycaps</td>
<td>Respond to user input to close circuit and produce characters on screen.</td>
</tr>
<tr>
<td>5</td>
<td>5 Internal Phillips Screws</td>
<td>Secure PCBA and ground components.</td>
</tr>
<tr>
<td>6</td>
<td>14 External Phillips Screws</td>
<td>Attach top housing to bottom housing.</td>
</tr>
<tr>
<td>7</td>
<td>Metal Baseplate</td>
<td>Ground circuitry, stabilize components, and provide added weight.</td>
</tr>
<tr>
<td>8</td>
<td>Conductive Trace Film Sheets</td>
<td>Provide circuitry for key press actuation.</td>
</tr>
<tr>
<td>9</td>
<td>Rubber Dome Layer</td>
<td>Compress under keycap to close circuit and signal a key press.</td>
</tr>
<tr>
<td>10</td>
<td>PCBA</td>
<td>Provide electronics necessary for keyboard functionality.</td>
</tr>
<tr>
<td>11</td>
<td>USB Cable</td>
<td>Connect keyboard PCBA to computer.</td>
</tr>
<tr>
<td>12</td>
<td>Metal PCBA Bracket</td>
<td>Provide contact pressure across PCBA to ensure it is secure and aligned.</td>
</tr>
</tbody>
</table>

Non-destructive disassembly of this keyboard was possible, except for the removal of a couple adhesives that, unsurprisingly, did not stick as well when reattached. Four of the screws on the
bottom housing were beneath adhesive—two of them under sticky keyboard feet and two of them under the device information label. For this particular device, one of the keyboard legs was missing, which is likely the reason it was discarded.

4.5 KEYBOARD DESIGN OVERVIEW

Initial brainstorming for this design started by determining which keyboard components from the waste keyboard could be reused. After consideration, the components selected for reuse were components 7-12 from Table 7. The reason for this was the rest of the components could be redesigned to address potential keyboard failure modes. This design assumes the electronics from the selected waste keyboard are functional.

3D printing was selected as the manufacturing method for components that are not available OTS because of the relatively widespread use of 3D printers for at home plastic manufacturing. This design will employ a “piggybacking” design approach where new 3D printed components are added (and previous components removed) to extend the useful life of the electronics. It was important to consider the manufacturing method early in the design process to ensure all components are designed for printability.

It is worth noting that this project will use a Bambu Lab P1S 3D printer, shown in Figure 14.

Figure 14. Bambu Lab P1S 3D Printer [63].
The tight tolerances and rapid print speeds possible with the Bambu P1S are integral to prototyping success. Without this precision and speed, it would be significantly more difficult to use 3D printing as the manufacturing method for a project such as this. The technical specifications for the Bambu Lab P1S are given in Appendix C.

Most of the failure modes from Table 4 can be addressed by creating a modular design and providing the necessary replacement parts. However, it is also desirable to address some of the common customer complaints from Table 5 to increase the likelihood that individuals would want to use and repair this product (see section 2.1.1 Repairable Design Guidelines). The major complaints selected to address were “unpleasing aesthetic” and “mushy keys.” To improve upon aesthetics, the design should be pleasing and timeless. Since the housing components will be 3D printed, they could be made in any color, and users could further customize the files before printing to fit their preferences.

The mushy keys can be improved by creating a mechanism to interface between the keycap and the rubber dome keyboard that decreases perceived mushiness. After ideation (see Appendix D), the chosen design concept for the interfacing mechanism is to adapt OTS mechanical keyboard switches to actuate the rubber dome. This would introduce a spring mechanism to the keyboard press, improving tactility and reducing mushiness. Ultimately, this would give users of this transformed membrane keyboard an improved typing experience by employing some of the same strategies used in mechanical keyboards. The advantage of using mechanical keyboard switches for this mechanism is that they include a spring, top housing, and keycap integration piece in an all-in-one part, reducing both design time and the number of components necessary to purchase or print. Additionally, the components of a keycap/spring actuation mechanism are small, tight-tolerance parts. It would likely be tedious to 3D print this many small components for a full keyboard build.
To adapt the mechanical switch to fit a rubber dome keyboard, the switch is first dissected by popping off the bottom of the switch encasing that usually electrically and mechanically connects the switch to the PCBA. With the bottom of the housing removed, four plastic extrudes are accessible. A baseplate is introduced that has receptors for these plastic extrudes to allow a snap fit. There is also a cylindrical extrude for stability and alignment that matches the locations of the rubber domes. A sketch of the design for the keycap actuation mechanism is shown in Figure 15.

![Figure 15. Sketch of Keycap Actuation Mechanism.](image)

This concept is advantageous because it would improve the typing experience for the user (reducing “mushiness”), while providing a keycap actuation method that doesn’t involve 3D printing numerous small components. Furthermore, standard mechanical keyboard keycaps can fit into these switches. This means users could select and purchase any existing keycap set for their keyboard, further improving customizability. Users could also 3D print their own keycaps or replacement keycaps (with provided files) if they prefer. On the other hand, the disadvantage of this design concept is that it has significant technical risk. There are not currently any keyboards that operate this way, so it was unknown if this mechanism would have the required functionality. An overview sketch of the full design is shown in the Figure 16. Additional ideation and product design sketches can be found in Appendix D.
To further detail the components used in this design (in addition to components 7-12 from Table 7), Table 8 lists each component, its corresponding function, and the related failure mode(s) that the component can address. The failure modes in parentheses did not come from topic modeling, but they may still be relevant.
Table 8. Keyboard Design Components.

<table>
<thead>
<tr>
<th>Component Number</th>
<th>Component</th>
<th>Function</th>
<th>Related Failure Mode(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Keyboard Housing Base</td>
<td>Protect, stabilize, and align all components.</td>
<td>Wobbly keyboard base. Unpleasing aesthetic. Too light. (Cracks/damage.)</td>
</tr>
<tr>
<td>2</td>
<td>Keyboard Baseplate</td>
<td>Hold mechanical switch components in place and align them with rubber domes. Protect membrane and film sheets.</td>
<td>Keys sticking. (Water damage.)</td>
</tr>
<tr>
<td>3</td>
<td>PCBA Cover</td>
<td>Protect PCBA.</td>
<td>(Water damage.)</td>
</tr>
<tr>
<td>5</td>
<td>Keycaps</td>
<td>Provide contact surface for user input to actuate keys.</td>
<td>Keys sticking. Letters wearing off the keys. Missing letters/typing errors. Lost keycaps.</td>
</tr>
<tr>
<td>6</td>
<td>Fasteners</td>
<td>Secure, align, and ground components.</td>
<td>(Misalignment.)</td>
</tr>
</tbody>
</table>

There are two aspects of this design that require significant design work: developing the keycap actuation mechanism and successfully aligning the baseplate to the rubber dome keycaps and all other layers. Thus, the strategy was to prototype and test these design aspects separately through iterative design and rapid prototyping to ensure their functionality before constructing a full assembly. The following sections further detail the prototyping and testing work for these components independently and their integration into a full assembly prototype.

4.6 COMPONENT DESIGN AND PROTOTYPING

This section describes the detailed design and prototyping for the keyboard components individually before integration. The components in this section are ordered from highest technical
risk/most design work required to lowest technical risk/least design work required. The first two components discussed (the keycap actuation mechanism and the keyboard baseplate) require significantly more design work than the rest of the components.

4.6.1 KEYCAP ACTUATION MECHANISM

After the design given in Figure 16 was decided upon, the next step was to make an initial proof of concept prototype. (Brainstorming sketches for the keycap actuation mechanism are given in Appendix D.) To determine if this actuation mechanism would work in practice, a 3D-printable part was designed and prototyped to test the actuation mechanism on one rubber dome. The CAD model for the test part is given in Figure 17.

![Figure 17. Actuation Mechanism Test Piece CAD.](image)

As with all 3D-printed components for this project, the actuation mechanism test parts were printed on a Bambu Labs P1S 3D printer. Additionally, a Gateron green switch was disassembled to make use of its components, as described in section 4.5 Keyboard Design Overview. This required popping off the bottom of the housing by inserting a flathead screwdriver in the notches on both sides of the switch. The components of the switch used in this design and the 3D-printed actuation mechanism test piece are shown in Figure 18.
Figure 18. Components Used from Switch and 3D-Printed Actuation Mechanism Test Piece.

Following a few dimension modifications for the cylindrical extrude and switch receptors, the test piece was attached to the switch housing. The spring was placed internally on top of one of the rubber domes. When held down in place (see the right image of Figure 19), pushing down on the green switch worked consistently to actuate the key.

Figure 19. Actuation Mechanism Proof of Concept Test.
The feel of the keycap press was anecdotally “better” (i.e. less mushy) than a typical membrane keyboard but not as good as a typical mechanical keyboard. However, this test indicated a promising start for the actuation mechanism. At this point, with preliminary feasibility proven, work on the actuation mechanism slowed. Development time was spent on the other components. Further actuation mechanism refinements would wait until after component integration.

4.6.2 KEYBOARD BASEPLATE

The most difficult aspect of the keyboard baseplate was alignment. The final baseplate design needed to have a cylindrical extrude and switch receptors (see Figure 17) aligned with each rubber dome on the sheet. Before adding the switch receptors, the alignment design and testing was done with just the cylindrical extrudes. Initially, a photo of the rubber dome layer (taken as level as possible) was imported into Autodesk Fusion 360 (the chosen CAD software for this project). In Fusion 360, the image was scaled, and sketches were made on top of the image to locate the rubber domes. The image with the final alignment sketch is shown in Figure 20.

![Figure 20. Rubber Dome Layer and Alignment Sketch.](image)

This was useful to begin dimensioning, but the perspective of the camera lens caused a discrepancy between the true dimensions and those extracted from the image. To correct this, careful measurements of the rubber dome spacing were necessary. This turned out to be a difficult process because the rubber domes do not follow a consistent pattern (spacing or x/y alignment)
across the keyboard. There were some rubber domes spaced evenly and aligned horizontally (such as the alphabet keys), but many were not, requiring many iterations of testing, measuring, and re-printing various sections. The CAD model for the baseplate used during the alignment stage is shown in Figure 21.

![Baseplate Alignment CAD Model](image1)

Figure 21. Baseplate Alignment CAD Model.

Figure 22 shows a few of the alignment test pieces for different parts of the membrane.

![Baseplate Alignment Test Pieces](image2)

Figure 22. Baseplate Alignment Test Pieces.
The left image from Figure 22 shows the first printed piece to test the alignment of a rectangle of 12 rubber domes. The image on the right shows an alignment test piece for the middle section. Aligning the extrudes was done by moving from right to left across the membrane to ensure each test piece had some extrudes already aligned from the previous piece, while also minimizing the amount of material used for each test. Despite these efforts to minimize waste, the quantity of alignment parts used for this process caused me to put an ABS filament recycler at the top of my list of future projects.

Once the cylindrical extrudes were aligned across the baseplate, the four rectangular receptors for the switch were added for each rubber dome. For printability, the baseplate was split into two separate parts that can be aligned together. At this stage, the baseplate was complete until future modifications during component integration (to accommodate fasteners and locating extrudes from the housing base). This is described in section 4.7 Full Assembly Design and Prototyping.

4.6.3 KEYCAPS

As a starting place, the keycap design focused only on the smallest size of keycap (used for the alphabet and numeric characters, arrow keys, and function keys, but not the space bar, tab key, backspace, etc.). The basic structure for these keycaps was modeled after existing mechanical keyboard keycaps—a top profile for typing and an extruded crossbar piece with a cutout that presses into the top of mechanical keyboard switches. Once the desired tolerances for a tight sliding fit in the crossbar piece were achieved, the shape of the keycap profile needed to be determined.

Designing the keycap profile started by testing out a couple different shapes and iteratively refining them until they seemed comfortable to type on and aesthetically pleasing. Figure 23 shows the original keycap CAD model (top) compared to the final design (bottom).
As shown in the figure, the final keycap design had noticeable improvements in profile curvature, size, and edge smoothing, which resulted in a better typing feel and visual appeal. Once the final design was selected, a set of keycaps was 3D printed out of ABS for the alphabet keys (shown in Figure 24).

Figure 23. First Keycap Design (Top) and Final Keycap Design (Bottom).

Figure 24. 3D-Printed ABS Keycaps.
The keycaps were placed on a mechanical keyboard and submitted to long term testing to evaluate how they compared to professionally produced keycaps. Figure 25 shows the clear ABS keycaps in use on a mechanical keyboard.

![Clear ABS Keycaps in Use.](image)

Figure 25. Clear ABS Keycaps in Use.

These ABS keycaps were used daily for over six months (including to type the majority of this document) with no noticeable decline in performance. After the addition of letters and modifications to fit the larger keys (see section 4.8 Upcoming Design Refinements), they would be ready for integration into a full keyboard build.
4.6.4 KEYBOARD HOUSING BASE

Similar to the baseplate, the most challenging aspect of the keyboard housing base design was component alignment. The housing base needed to secure and align the PCBA, circuit film layers, metal plate, and rubber dome layer. The existing housing for the KU-1469 keyboard used circular extrusions from the housing base that went through all components to hold them in place (in addition to screws securing the PCBA and metal plate). This same approach was used in this design. Cylindrical extrudes were created to fit within the pre-existing holes in the plastic film sheets, rubber dome layer, and metal plate. The CAD model for the housing base from the early design stages is shown in Figure 26. The curved line in the center of the part shows where the housing was split into two components for 3D printing.

![Figure 26. Early Design of Housing Base.](image)

Although this alignment was significantly less tedious than the baseplate alignment, it was done with a similar approach. A small piece of the housing base consisting of just the far right of the keyboard was printed and tested a couple times until the components were aligned successfully.
Then, the right and left halves of the full housing could be printed. Figure 27 shows the first housing base alignment attempt.

![Figure 27. First Housing Base Alignment Test.](image)

After improvements, the right section of the housing base successfully aligned the PCBA, metal plate, plastic film layers, and rubber dome layer. This was done with screws and cylindrical extrusions. This is shown in Figure 28 along with the test piece for the keycap actuation mechanism.
Following this design work, the housing base was ready for component integration where there would be additional necessary design modifications (such as including fasteners for the baseplate).

4.7 FULL ASSEMBLY DESIGN & PROTOTYPING

To integrate the components into a full keyboard build, a series of prototypes was created, each one progressing closer to a functional keyboard. After each prototype, thorough notes were taken on the prototype performance and necessary design modifications. After components were redesigned as needed, another prototype was created and evaluated. The end goal was a keyboard that met all the requirements in Table 6, but the focus for early testing was successful keycap actuation across the keyboard. This turned out to be more difficult than originally anticipated.

The following sections detail each of these prototypes with descriptions of their design modifications and the insights from each build. These prototypes were called “Functional Prototype Tests” because they were focused on testing keycap actuation functionality.
4.7.1 FUNCTIONAL PROTOTYPE TEST 1

Functional Prototype Test 1 (FPT1) was mostly focused on alignment because it was the first time all components were integrated. The prototype is shown in Figure 29. A few keycaps (both 3D-printed and from a manufactured keycap set) were used to try and test the keycap actuation mechanism.

![Functional Prototype Test 1](image)

Figure 29. Functional Prototype Test 1.

Without screws to secure the baseplate, testing the keycap actuation mechanism was difficult because it required pressing down the baseplate. For this reason, and due to alignment issues, a functional test of the actuation mechanism was not realistic. Significant design modifications were needed. Table 9 provides the specific takeaways from this prototype, as well as the corresponding action items to address them.
Table 9. Functional Prototype Test 1 Results.

<table>
<thead>
<tr>
<th>Result</th>
<th>Action Item</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holes to align PCBA are slightly off.</td>
<td>Take additional measurements of the PCBA hole and adjust the housing base hole dimensions.</td>
<td>HIGH</td>
</tr>
<tr>
<td>Baseplate does not stay in place when switches are added (due to spring force).</td>
<td>Extend the housing base and baseplate components to accommodate fasteners or magnets to secure the baseplate.</td>
<td>HIGH</td>
</tr>
<tr>
<td>Receptor holes do not fit new box of Gateron green switches.</td>
<td>Investigate why the two boxes of Gateron green switches are not the same. For now, use switches from the original box and move forward.</td>
<td>MED</td>
</tr>
<tr>
<td>Rubber dome layer is difficult to align.</td>
<td>Add additional extrudes on the housing base that match with holes on the rubber dome layer.</td>
<td>LOW</td>
</tr>
</tbody>
</table>

The items in the table listed as having low priority are those not critical for functionality testing. They should be addressed in the final design, but do not need to be addressed to complete a functional prototype. The items with medium priority are those that should be addressed, but there is another way to move forward that avoids the issue for the time being. The items with high priority are those that need to be addressed to move forward with the next prototype.

4.7.2 FUNCTIONAL PROTOTYPE TEST 2

After fixing the holes for PCBA alignment and adding fasteners, the design was ready for another test. FPT2 is shown in Figure 30. The chosen shape for the baseplate perimeter was a curved edge to match the other curves incorporated in this design (the split lines for printing on the housing
Only the right half of the keyboard assembly was used for this test to reduce filament consumption. There was much to learn from just the right half of the keyboard assembly.

Unfortunately, there was a slight alignment mishap in Fusion 360, causing the top hole and the extrudes on the housing base to be offset from the baseplate. (Note: due to the need for frequent alignment adjustments, the extrudes were not extended to their full height for easier testing.) Despite this issue, the test still had useful takeaways. These are given in Table 10.

Table 10. Functional Prototype Test 2 Results.

<table>
<thead>
<tr>
<th>Result</th>
<th>Action Item</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseplate edge curvature does not have a “timeless,” widely appealing aesthetic.</td>
<td>Remove curvature from the baseplate edges.</td>
<td>LOW</td>
</tr>
<tr>
<td>Seems like baseplate is sitting too high on the rubber domes.</td>
<td>Move the housing base extrudes for the screws .050” down.</td>
<td>HIGH</td>
</tr>
<tr>
<td>Alignment mishap with top screw hole and extrudes on housing base.</td>
<td>Fix alignment in Fusion 360.</td>
<td>HIGH</td>
</tr>
<tr>
<td>Keycap actuation mechanism not functioning.</td>
<td>Try moving the baseplate down and adding more fasteners.</td>
<td>HIGH</td>
</tr>
</tbody>
</table>
Most notably, this test raised concerns about the keycap actuation mechanism. Despite previous testing that indicated functionality for one rubber dome, the mechanism did not appear to scale easily. The key would not register every time a keycap was pressed. Pushing down on the baseplate would sometimes fix this, but then other keys would often be activated, leading to a spew of unwanted characters. At this point, this design concept was questioned. Maybe the addition of a plate directly on top of the rubber dome layer would inevitably lead to keycap actuation inconsistency? It was possible the test on one rubber dome only worked because the plate was pressed down directly around the dome, which would be unrealistic in practice. At this point, it was not obvious why the keycap actuation mechanism was not working. There were a couple clear improvements to be made (increasing the screw extrude height on the housing base and adding more fasteners), so it was decided to move forward. The hope was to continue prototyping to gain a better understanding of what was going wrong.

4.7.3 FUNCTIONAL PROTOTYPE TEST 3

Ten screws were added (to just the right side) for FPT3. Additionally, the extrudes for the screws in the housing base were lowered by .050” to place the cylindrical features lower on the rubber dome layer. The result of these changes is shown in Figure 31.

![Figure 31. Functional Prototype Test 3.](image)
As shown, the alignment mishap was fixed. Additionally, the screws and positioning of the cylinders did improve keycap actuation functionality, but it was still inconsistent. It took a slow, strong press in the center of the keycap to consistently actuate the key. To further explore this issue, a variety of ad hoc modifications were performed on the actuation mechanism. Small pieces of paper were placed on top of the cylindrical extrudes to see if changing the height of the baseplate relative to the rubber dome layer helped with key activation consistency. This did not make a noticeable difference, although moving the baseplate too far from the membrane had a negative effect. Additionally, the springs were cut in half to determine if decreasing the spring length would make keycap actuation easier. This also did not seem to help the problem. However, there could be room for further testing with different spring lengths and stiffnesses. The results for FPT3 are given in Table 11.

Table 11. Functional Prototype Test 3 Results.

<table>
<thead>
<tr>
<th>Result</th>
<th>Action Item</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keycap actuation is not consistent and requires a slow, strong press in the center of the keycap.</td>
<td>Print the left housing base and baseplate pieces to do a full keyboard test. This will allow for a test of the full base alignment as more ideas to solve the actuation problem are brainstormed. Additionally, typing with the alphabet keys may be useful to further diagnose the keycap actuation issues.</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

As described in the table, it was decided to proceed forward with a full keyboard build to further evaluate the issues with the actuation mechanism and test full keyboard alignment.

4.7.4 FUNCTIONAL PROTOTYPE TEST 4

FPT4 involved adding the left half of the housing base and baseplate to the printed parts from FPT3. The full keyboard is shown in Figure 32.
As hoped, adding the left side to the prototype did result in a few additional insights related to integration of the two sides and alignment. Additionally, further experimenting with typing on the full keyboard and examining the actuation issue gleaned a few hypotheses for why the actuation mechanism was functioning poorly. These hypotheses are as follows:

1. The spring is too long (but half the spring was too short), such that it is already buckling in its uncompressed state.

2. The switch stem that moves through the switch housing is too short (or starts too far away), such that it does not completely (or consistently) compress the rubber dome.

3. The switch stem does not always compress the rubber dome in the center, meaning that it sometimes folds the rubber dome instead of fully compressing it.

As a quick design modification to test the second hypothesis, masking tape was added to the end of the switch stem as shown in Figure 33.
With masking tape of the right length, this provided a tremendous improvement. The keys were activated consistently, where every press on the keycap resulted in the corresponding character appearing on screen. With too long of masking tape, the key actuation was inconsistent or would not work at all. There was also a trade-off between key travel (and thus typing feel) and key actuation consistency. After a couple tries with different lengths of masking tape, it seemed that a balance could be struck where the key is actuated consistently and there is still some key travel. It is worth noting that there was significantly less travel than the original mechanism. This typing experience is not similar to that of a mechanical keyboard, even though it uses mechanical keyboard switches. However, the other benefits of adapting mechanical keyboard switches still apply: OTS components are used and standard keycap sets can be easily attached. It may also be possible to further improve the typing experience to increase tactility and decrease “mushiness.”

Future steps include modifying the design geometry to more thoroughly test these hypotheses and develop a fully functioning prototype (without ad hoc masking tape adjustments). This could involve changing the height of the switch housing relative to the rubber dome (so the switch stem starts closer to the dome) or making an extension cap that would fit directly onto the stem (though this would be a small, tedious component and require additional assembly). The benefit of an end cap is that it could also increase the contact area between the stem and rubber dome, providing a more even actuation pressure distribution and reducing the likelihood of the rubber dome bending out of place. Table 12 below provides a summary of the results from FPT4.
Table 12. Functional Prototype Test 4 Results.

<table>
<thead>
<tr>
<th>Result</th>
<th>Action Item</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keycap actuation is still inconsistent (same as FPT3).</td>
<td>Test the stated hypotheses to implement design modifications that achieve functionality comparable to what was achieved with the masking tape adjustment.</td>
<td>HIGH</td>
</tr>
<tr>
<td>Hole in metal baseplate does not align to corresponding extrude and hole on housing base.</td>
<td>Take measurements of the alignment issue and modify the dimensions in Fusion 360.</td>
<td>MED</td>
</tr>
<tr>
<td>Alignment extrudes from housing base are a bit off from the metal plate, plastic film sheets, and membrane layer.</td>
<td>Take measurements of the alignment issue and modify the dimensions in Fusion 360.</td>
<td>MED</td>
</tr>
<tr>
<td>The left and right sides have a small gap between them when pressed together (and could be more securely attached).</td>
<td>Add a slot or mating feature (possibly with a fastener directly through it) to close the gap and better secure the housing base.</td>
<td>MED</td>
</tr>
</tbody>
</table>

Although more design work is needed, FPT4 was an exciting breakthrough. It proved that this design concept is still promising, and, after the necessary modifications, an actuation mechanism that fully functions across the keyboard is on the horizon.

4.7.5 FUNCTIONAL PROTOTYPE 1

Following the functional prototype tests (FPT1-4) where the end goal was functionality, the next stage of prototyping is needed to refine all other design aspects. The first prototype in this new phase is Functional Prototype 1, which is currently in progress. The assembly CAD for this prototype is given in Figure 34.
The best method for improving the keycap actuation mechanism is still being evaluated, but Functional Prototype 1 will have a functioning keycap actuation mechanism for the entire keyboard. As of now, an end cap for the stem has been created and tested with the same success achieved through the masking tape modification. The end cap both extends the length of the extension piece and increases the contact area with the rubber dome. Figure 35 shows the 3D-printed end cap attached to the switch stem.
Additionally, there are other necessary steps to ensure the keyboard requirements are met. The following section, 4.8 Upcoming Design Refinements, details the design work needed for Functional Prototype 1 and any consecutive prototypes. Once the final design has been refined, it will successfully address many of the failure modes and complaints identified from customer feedback, resulting in a more repairable keyboard. Table 13 summarizes how this design addresses the failure modes and complaints. This table is a reiteration of Table 4 and Table 5, though this time it describes the implemented design solutions.

Table 13. Failure Modes and Complaints Addressed in Final Design.

<table>
<thead>
<tr>
<th>Failure Mode/Complaint</th>
<th>Possible Causes</th>
<th>Implemented Design Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keys sticking</td>
<td>Dust and debris impairing key travel. Rubber dome gets stuck in the down position. Too much friction in plastic sliding mechanism. Rubber dome is not pressed down in the center.</td>
<td>Entire keyboard (including keycaps) is easy to disassemble to allow for cleaning. Spring mechanism reduces likelihood that rubber dome will be stuck in compressed state.</td>
</tr>
<tr>
<td>Letters wearing off the keys</td>
<td>Application of letters does not hold up to prolonged use.</td>
<td>TBD (design refinement still needed)</td>
</tr>
<tr>
<td>Wobbly keyboard base</td>
<td>Limited structural rigidity due to thin plastic. Few contact points with the supporting surface. Uneven or unstable keyboard legs, etc.</td>
<td>The base has full contact with the work surface and the thickness can be easily increased if rigidity is a problem. There are no keyboard legs in the current design.</td>
</tr>
<tr>
<td>Keyboard legs breaking</td>
<td>Legs are blocked from rotating a full 360 degrees, so if they are over extended, they easily snap (shear or bending failure). Legs are made of thin plastic. Leg attachment to keyboard has rigid geometry that results in stress concentrations.</td>
<td>N/A (no keyboard legs in the current design)</td>
</tr>
<tr>
<td>Missing letters/typing errors</td>
<td>Feedback from key press is not tactile enough (user cannot immediately tell if a key is registered). Keycap actuation requires too much force. Keyboard cannot register</td>
<td>Spring mechanism improves tactility to reduce typing errors. Modifications to switch stem (such as the extension piece in Figure 35) ensure it is long enough and has sufficient contact area to fully</td>
</tr>
<tr>
<td>Issue</td>
<td>Description</td>
<td>Solution</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Multiple key presses at the same time.</td>
<td>Rubber dome is not compressed fully or is stuck down. Rubber dome is not actuated in its center.</td>
<td>Compress the rubber dome in its center.</td>
</tr>
<tr>
<td>Mushy keys</td>
<td>Compressing directly on the rubber dome is innately “mushy.”</td>
<td>Addition of spring through the keycap actuation mechanism improves tactility and decreases “mushiness.”</td>
</tr>
<tr>
<td>Lost keycaps</td>
<td>Keycaps don’t stay securely connected to keyboard housing. In school settings, it may be fairly common for children to remove keycaps.</td>
<td>Replacement keycaps can be easily printed or purchased. This keyboard is compatible with standard mechanical keyboard keycap sets.</td>
</tr>
<tr>
<td>Unpleasing aesthetic</td>
<td>Consumers differ in aesthetic values and their preferences may change over time. New product marketing is always trying to catch the consumers’ eyes, so old devices might not look as flashy or be as pleasing to use.</td>
<td>The keyboard aesthetics are elevated from the original membrane keyboard design and color scheme. Additionally, the part files and colors are customizable.</td>
</tr>
<tr>
<td>Too light (doesn’t feel sturdy)</td>
<td>Rubber dome membrane keyboards typically have all plastic encasings without added weights.</td>
<td>This was not specifically addressed, but weights could be added if desired.</td>
</tr>
</tbody>
</table>

The final design is a repairable keyboard, in part because it directly addresses these failure modes and complaints. The likelihood of mechanical failure is reduced, and any failures that do occur have been anticipated and repair should be feasible. Furthermore, the keyboard requirements require implementing the design for repairability guidelines outlined in section 2.1.1. This ensures general design for repairability principles are applied.

**4.8 UPCOMING DESIGN REFINEMENTS**

To refine Functional Prototype 1, additional design work is needed to meet the requirements in Table 6. There are also optional design refinements that do not directly relate to the requirements, but they may enhance the project. These are both described in the following sections.
4.8.1 REQUIRED DESIGN REFINEMENTS

The design refinements needed to meet the keyboard requirements are given in Table 14, where each requirement is listed along with the modifications needed before testing and requirement verification.

Table 14. Design Refinements Needed for Keyboard Requirements.

<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
<th>Description</th>
<th>Required Design Refinements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Functionality</td>
<td>The keyboard works comparably to other functioning membrane or mechanical keyboards—an average keycap press results in the corresponding letter appearing on screen.</td>
<td>Implement a functioning keycap actuation mechanism for the entire keyboard. Make 3D-printed keycaps for the rest of the keys. Add labels to all of the keycaps.</td>
</tr>
<tr>
<td>2</td>
<td>Secure Component Alignment</td>
<td>Components do not move relative to each other in the keyboard housing when the keyboard is moved or jostled.</td>
<td>Add additional extrudes on the housing base that match with holes on the rubber dome layer.</td>
</tr>
<tr>
<td>3</td>
<td>Repairable After Typical Fall</td>
<td>After a fall from a typical desk surface, the keyboard can be repaired.</td>
<td>Add a slot or mating feature (possibly with a fastener directly through it) to close the gap and better secure the housing base. Add a PCBA cover.</td>
</tr>
<tr>
<td>4</td>
<td>Waterproof to Typical Spill</td>
<td>After liquid from an average drinking cup spills on the keyboard, there is no water ingress through the PCBA enclosure and the keyboard still functions</td>
<td>Add a PCBA cover. If the test fails, a gasket or sealant could be added.</td>
</tr>
<tr>
<td>5</td>
<td>Repairable Design</td>
<td>Keyboard should follow the design for repairability guidelines outlined in section 2.1.1.</td>
<td>Add identifying marks to components where necessary. Write a device repair/troubleshooting manual.</td>
</tr>
<tr>
<td>6</td>
<td>E-Waste Reuse</td>
<td>Keyboard electronic components are</td>
<td>None.</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Off-the-shelf Component Usage</td>
<td>Additional keyboard components (not those reused) are OTS components whenever possible.</td>
</tr>
<tr>
<td>----</td>
<td>---</td>
<td>------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>8</td>
<td>Addresses Common Mechanical Failure Modes</td>
<td>Keyboard design addresses the failure modes identified from topic modeling results (see Table 13).</td>
<td>Determine a good solution for adding letters to the keycaps without them wearing off quickly. Continue refining the keycap actuation mechanism to improve tactility.</td>
</tr>
<tr>
<td>9</td>
<td>Effective Keyboard Build Instructions</td>
<td>The keyboard build instructions are sufficient to guide a non-engineering individual through the build process with positive user satisfaction.</td>
<td>Write keyboard build instructions.</td>
</tr>
</tbody>
</table>

In addition to these required changes, there are numerous optional design modifications that will be explored and implemented to further improve the keyboard.

### 4.8.2 OPTIONAL DESIGN REFINEMENTS

A list of optional design refinements (in no particular order) that could enhance the keyboard is as follows:

- Adjust keycap set to have different profile shapes depending on keyboard position for improved ergonomics.
- Refine the slope on the inside of the housing base (increase/decrease and evaluate ergonomics).
- Experiment with ABS post-processing (with acetone) for smoother keycap surfaces.
- Explore versatility of this design for other similar keyboard models.
- Make it easier to pop the switch housings off the baseplate.
- Use magnets instead of screws to secure the baseplate to the housing base.
- Revise screw design to only use the screws from the original KU-1469 housing (unless magnets are used) so purchasing additional screws is not required (originally, larger screws were used because a greater quantity of screws was needed and maximum clamping force desired).

- Implement heat set inserts into the housing base for screws (unless magnets are used) so plastic threads do not tear out after repetitive use.

- Improve snap fit of switch housings onto baseplate (add chamfers, etc.).

- Change the edge pattern on the baseplate that separates the two sides.

- Adjust the geometry for the USB cable so it snaps in place or sits nicely.

- Experiment with creating build plans and prototypes out of different materials instead of only using 3D-printed parts. At the very least, demonstrate on the website that users can tailor the design concept of DIY e-waste reuse to fit their personal artistic preferences and skillsets.

As described in the last bullet point, future work could explore making these components out of different mediums. There has already been some creative effort put into this, including making custom wood keyboard bases that could house reused keyboard electronic components in the future. Figure 36 shows a few photos of creating the wood keyboard bases. Two keyboard bases were made, one at a 75% layout and one at 100%.
Additionally, a project is underway to make cast metal keycaps. Using the final keycap CAD model from Figure 23, a “keycap tree” was created for lost-PLA investment casting. The keycap tree was printed out of PLA and used to make a mold with investment plaster. Once cycled through heat treatment in an indoor furnace and outdoor kiln, the PLA burned out, leaving a cavity for molten metal to fill. This resulted in a metal keycap tree. This process was performed.
twice, once with aluminum and once with brass. Post-processing is still needed to separate the keycaps from the tree and smooth the edges. Figure 37 shows a few photos of the casting process.

![Figure 37. Keycap Casting.](image)

The hope with these projects is to demonstrate the many opportunities for creative projects that transform e-waste into “high-quality, durable products that people will want to repair and continue using” (from section 2.1.1 Repairable Design Guidelines). Additionally, these projects exemplify that DIY electronic reuse does not have to involve 3D printing and can fit a variety of artistic preferences and skillsets.
5. SHARING RESULTS

With the goal of spreading knowledge and enthusiasm about repairable design, the work from this thesis will be shared in a couple of ways.

The topic modeling work described in Chapter 3 has been accepted (in the form of a conference proceedings paper) for presentation at the International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC-CIE). The paper can be found in Appendix B. The conference will be held in Washington D.C. in August of 2024. Additionally, after the completion of this thesis defense, work will begin to expand this conference paper into an American Society of Mechanical Engineers (ASME) journal paper with the hopes of publication.

Additionally, a website has been created to share this project and the final keyboard design. Once the keyboard design is refined, build instructions and downloadable part files will be provided for anyone who is interested. The website URL will be www.makes-and-breaks.com once it is published. A screenshot of the in-progress website is shown in Figure 38.

![Website Screenshot](image)

Figure 38. Website Coming Soon Page.
This project has also been shared with the Cal Poly community through an article published in the Cal Poly News on May 5th, 2024, titled “Engineers Embrace Repair Culture as New Law Takes Shape in California [64].” The full article can be found in Appendix E. Figure 39 shows some of the photos captured during the interview.

![Figure 39. Photos from Cal Poly News Interview.](image)

Excitingly, Dr. Song plans to continue design for repairability research at Cal Poly through his Data-Driven Design Methodology Lab (D3ML) [65]. Future undergraduate and graduate students will continue to share their enthusiasm for repairability within the Cal Poly community and beyond.
6. CONCLUSION

This project has explored design for repairability through topic modeling research for design tool development, as well as hands-on product design. The result is a body of work that is relevant to researchers, design tool developers, and sustainable (specifically repairable) product designers.

From a research and design tool perspective, this work shows the usefulness of topic modeling as a potential tool for designers to improve product repairability. This research provides a methodology for retrieving and examining repairability-related product reviews to identify failure mode trends across consumer electronics. The keyboard example gives tangible results indicating the value in this approach, but it is only the tip of the iceberg. There is tremendous opportunity for applying this methodology across many other categories of products. Additionally, future work transforming a methodology such as this into an easily accessible design program or consumer reference would be monumental.

The keyboard product design case study illustrates the application of topic modeling results. This design shows how topic modeling can uncover device-specific insights to make products more repairable. Additionally, it suggests another avenue for sustainable product development—design for electronic waste reuse. This keyboard design uses the PCBA, USB cable, baseplate, plastic film layers, and rubber dome layer from an existing waste membrane keyboard. In this way, this design models a “piggybacking” approach where new components are added to extend the product lifespan. This same design approach could be applied across the consumer electronics industry, offering open-source designs and instructions, DIY build kits, and/or full products to the public.

The immediate next steps for this project are to finalize the keyboard design and share it online. The hope is to connect with repair-conscious individuals and product designers to inspire more designs that reuse electronic waste instead of requiring new components. After these next steps,
the opportunities for future projects within the sustainable/repairable design space are endless. I am personally interested in pursuing many of the areas for future work that I have mentioned. With this sentiment, I would like to conclude by promising there is more to come.
REFERENCES


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APPENDIX A. REPAIRABILITY KEYWORD LIST

adhe       wear
assembl    wobbl
bracket
break
broken
clamp
compatible
crack
desolder
disconnect
dismantle
error
fasten
fix
flathead
glitch
glue
hammer
knife
magnet
missing
pentalobe
phillips
pliers
pried
pry
puncture
repair
rewire
screw
seal
snap
solder
stick
tape
tear
troubleshoot
unplug
unresponsive
unsteady
APPENDIX B. IDETC-CIE 2024 PAPER

Proceedings of the ASME 2024
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC/CIE2024
August 25-28, 2024, Washington, DC

DETC2024-139384

USING DESIGN INSIGHTS FROM CUSTOMER FEEDBACK
TO ADVANCE DESIGN FOR REPAIRABILITY

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ABSTRACT
Design for repairability is an important design practice to increase the useful life of consumer products and decrease environmental impact. Current design for repairability guidelines include several practices that can be applied to a range of products across industries. However, these guidelines lack device-specific insights. This research proposes a methodology for extracting repairability design insights from customer feedback. This would help repair-conscious designers identify device components that may need redesign and prioritize components to offer as replacement parts. In this research, standalone computer keyboards are examined as a case study. This approach includes: a repairability keyword list to extract repairability-related phrases from Amazon product reviews. Topic modeling is performed with Non-Negative Matrix Factorization and BERTopic to access device failure modes, for computer keyboards. The repairability-related phrases are used to manually compare the repairability of these different keyboards. The proposed method identifies several failure modes for computer keyboards, such as sticky keys, Bluetooth disconnection, keyboard key breakdown, and instability in the keyboard base. This research indicates that topic modeling is a promising approach for obtaining repairability-related design insights from customer feedback.

Keywords: design-for-repairability, data-driven design, online reviews, customer feedback, topic modeling, product sustainability

1. INTRODUCTION
Electronic waste is environmentally costly for multiple reasons. The materials and manufacturing processes used to make consumer electronics generate a significant carbon footprint. This comes from the CO₂ emitted throughout the product life cycle, from mineral mining to end-of-life recycling. This results in embodied carbon in consumer electronics like laptops, cell phones, and tablets [1]. In 2020, an estimated 50 million metric tons of greenhouse gas emissions were from information and communications technology (ICT) devices, which was a 33% increase from the emissions in 2014. Another 50% increase is predicted by 2030 if current trends continue [2]. Additionally, 83% of e-waste ends up in landfills, forming mountains of hazardous waste where toxins pollute both soil and drinking water [2, 4].

The United States commonly exports this waste to developing countries, many of which do not have the necessary facilities or labor to extract value from these products. This poses a burden to the developing world, further widening the environmental inequality gap [2, 4]. Additionally, the metals required for electronics manufacturing (such as tin, cobalt, and gold) often come from mines in developing countries that offer workers (including children) inhumane conditions in exchange for less than a living wage [5]. This reality paints a gloomy picture of a complex problem that requires global collaboration across industries. This paper will present one of the primary ways designers can make a difference: designing products to be easily repairable, referred to as design for repairability [4].

The best way to keep electronics out of landfills is to continue using them. For consumers, this means repairing the devices they already own instead of replacing them. For designers, this means avoiding planned obsolescence and opting instead for designs that prioritize modularity, ease of disassembly, and the availability of replacement parts and device.
documentation [6]. Many principles of design for reparability can be widely applied to almost all devices (as discussed in the following section), but device-specific insights would further help designers. For example, it may be difficult to anticipate the common failure modes for a device or the most necessary replacement parts.

The right-to-repair movement aims to make repairable design practices commonplace, empowering consumers to fix their own devices instead of being forced to send them in for service or buy new ones altogether [7]. As of the beginning of 2024, twenty-seven U.S. states have some form of right-to-repair legislation [8]. In 2025, California, home to Silicon Valley, enacted legislation that requires manufacturers to “provide the means to diagnose, maintain or repair for seven years for products with a price point more than $100; three years for products under $100” [9]. The increasing prevalence of legislation such as this and growing momentum for the right-to-repair movement makes design tools for reparability even more desirable.

The goal of this research is to examine if customer feedback can help identify target areas for product redesign to improve device reparability and to indicate components to prioritize as available replacement parts. To achieve this, topic modeling is applied to Amazon customer reviews to identify reparability-related issues linked to specific electronic devices. Standalone computer keyboards are examined in this research as a case study. The main contributions of this work include:

- Methodology for retrieving and examining reparability-related product reviews to identify failure mode trends across consumer electronics.
- Illustration of the proposed methodology’s application in supporting design-for-reparability in the early stage of product design.

2. BACKGROUND

2.1 Design for Reparability

The fundamental goal of repairable design is to make it as easy as possible for consumers to fix their own electronics. This requires consideration throughout the product design process, from early design decisions that create modular components all the way to including device documentation, repair guides, and replacement parts available after product launch. According to the repair experts at iFixit, “highly repairable devices” should be designed to 1) disassemble and reassemble non-destructively and reversibly; 2) involve easily available tools for repair; and 3) prioritize access and repair of components that are either critical for device functionality or most likely to need repair [10].

The third criterion for highly repairable devices often requires specific knowledge about the performance of the device itself or similar existing products. One application of the methodology proposed in this paper is to help designers obtain these insights through customer feedback, so they can identify repair-critical components from similar existing products and improve their own product design. It is true, however, that many aspects of design for reparability can be widely applied across different devices. Design practices to enhance product reparability include, but are not limited to:

- Employ a modular design, allowing for easy component repair, upgrade, and recycling [1, 10-13].
- Use forward-thinking design approaches for components with fast evolutionary speeds (i.e., those that become obsolete the fastest) to enable future upgrades [11, 12].
- Use fasteners or magnets instead of adhesives whenever possible [10, 11, 13].
- Choose standard fasteners that can be removed with common tools [10, 13].
- Prioritize using off-the-shelf components instead of custom parts [10].
- Structure the device to minimize the number of steps it takes to remove critical components such as batteries [10, 12].
- Include identifying marks on devices to indicate key assembly information (such as arrows indicating proper orientation, labels for device make and model) to enable online research, etc. [10, 13].
- Provide a device service manual with replacement instructions for critical components, troubleshooting recommendations, necessary schematics and diagrams, etc. [10, 13].
- Ensure availability of reasonably priced device replacement parts from the original manufacturer or a trusted third party [10, 13].
- Use separable snap-ins instead of fused plastic [11, 13].
- Design high quality, durable products that people will want to repair and continue using [13].

There have been recent research efforts aimed at promoting product reparability. Reparability is closely linked to disassembly, as the ease of disassembling a product directly influences how easily it can be repaired. For example, with the goal of advancing design for repairability of mechanical products, [14] and [15] use a case study of electro-mechanical systems to introduce and apply an eco-design framework. In [14], researchers propose a methodology for establishing eco-design rules based on factors such as disassembly complexity, disassembly time, tooling, fasteners, and connectors. Efforts to achieve a circular economy (where resources are reused instead of discarded) are closely linked to device repair. The circular economy goal is not only dependent on device reparability, but also on consumer repair practices. Researchers have investigated both consumer behavior and product repair experiences. For instance, [16] integrated consumer repair
decisions and the deterioration process of components to evaluate the lifecycle of consumer electronics (e.g., laptops). Additionally, [7] explored consumer repair motivation and barriers through workshops, resulting in a repair motivation and barriers model that includes technical, emotional, and value aspects of repair.

One strategy to support product repairability is the identification of product failure modes. For example, [18, 19] use Support Vector Machines (SVM) to forecast the failure modes of medical devices from repair and maintenance records. This would aid in determining appropriate repair strategies. While this approach focuses on the identification of product failure modes, the approach presented in this work leverages customer feedback, which reflects the product experience of a range of users.

2.2 Topic Modeling

Topic modeling is a machine learning technique for discovering semantic topics within a collection of documents. Topic modeling can be used for summarization, classification, and retrieval of documents based on their content. It has proven to be effective in extracting insights from text data and has been implemented to support the early stages of product design [20, 21]. While several approaches exist for topic modeling, this research focuses on two methods: Nonnegative Matrix Factorization (NMF) and BERTopic. These methods are chosen for their efficiency in discovering semantic topics within short and unstructured text data, such as the Amazon product reviews used in this work [21].

2.2.1 Non-Negative Matrix Factorization (NMF)

Non-negative matrix factorization (NMF) is a method for topic modeling that has useful applications in text mining [25, 26]. NMF is a vector space method that makes use of non-negativity constraints to organize text data into meaningful categories [27]. In the NMF approach, a corpus of documents (e.g., product reviews) is represented as a word-by-document matrix that represents the frequency of words (rows) occurring in documents (columns). The matrix is factorized into 1) a word-by-topic matrix, whose row topic column is represented by a weighted distribution of words, and 2) a topic-by-document matrix, whose column document column is represented by a weighted distribution of topics. This allows for representations of documents as linear combinations of topics and topics as linear combinations of words, where all coefficients must be non-negative [27].

2.2.2 BERTopic

The second topic modeling approach used in this research is BERTopic, a methodology developed by Marco Grootendorst in 2019 [28]. In the BERTopic approach, the BERT transformer-based model is used to convert documents into vector representations called document embeddings. The dimensionality of the embeddings is reduced to form clusters of semantically similar documents where each cluster represents a topic. To extract the topic representation from each of these clusters, a class-based TF-IDF method is used [28]. BERTopic is novel in comparison to standard topic models (such as NMF) because it categorizes text without disregarding the “semantic relationships among words” [29]. While NMF builds topics based on a collection of words, BERTopic also takes into consideration the context in which the words are used. In this research, both NMF and BERTopic are applied to text from repairability-related Amazon product reviews to learn more about the specific keyboard issues most often discussed.

1.3 Related Work

Previous work from Sadding et al. [30] studied whether sustainable design insights could be obtained from Amazon product reviews using manual methods. The researchers also provided insights on machine learning approaches [31, 32]. Their manual method had three steps: 1) read customer reviews of Amazon Climate Pledge Friendly and standard products (e.g., cables, printers, laptops) and identify mentions of sustainability; 2) link sustainability mentions to specific product features; and 3) interpret reviews context to obtain sustainable design leads. The results showed both general design insights and those specific to the cables, printers, and laptops examined. General design insights indicated that reviewers discuss aspects of sustainability design and were most likely to mention sustainable aspects that directly benefitted them (such as component durability). Furthermore, the researchers concluded that the reviews could be interpreted to obtain leads for product designers, and they recommended future work in automating such a process [31].

From their paper on machine learning approaches [32], Sadding et al. outlined a framework for automating the process of obtaining sustainable design insights from customer reviews. They described a three-step process: 1) make use of natural language processing (NLP) to construct a machine learning pipeline for automation, 2) evaluate and improve the models as needed, and 3) scale and deploy the design tool, ideally through an accessible web platform [33]. The work in the present paper falls under the first objective with a narrowed focus on design for repairability, which is a subset of sustainable design.

Additionally, previous work has combined life cycle assessment (LCA) results with information from sustainability-related online reviews to obtain insights for sustainable design. In their paper [34], Sadding et al. discuss the advantage of using user feedback to provide precise design insights to complement more generic LCA findings. While LCA provides numerous uses for quantifying environmental impact, leveraging online customer feedback offers designers coarse inspiration to address specific sustainability concerns [34].

Other NLP work using Amazon reviews includes efforts to understand latent customer needs, which are needs “implied in the semantics of use cases” [21]. By contrast, explicit needs (those mentioned directly) are much easier for text mining approaches to handle. In their work to unveil latent customer needs, Zhou et al. used sentiment analysis as a first step in differentiating types of customer use cases. They used sentiment
analysis to evaluate whether users had positive or negative responses to specific product features [21]. Sentiment analysis can be applied similarly to sustainable design efforts because capturing user-maintained customer needs yields more comprehensive feedback. In the present research, sentiment analysis was used to separate product comments from praise.

Previous research has also applied topic modeling to failure mode identification of complex engineering systems, which is similar to using topic modeling to analyze repairability design. In their work, Anand et al. discussed applying latent Dirichlet allocation (LDA) topic modeling to NASA's Lessons Learned Information System. Their research goal was to determine if narratives surrounding engineering failures could be useful for failure mode prevention. Their approach extracted the cause, failure, and recommendation from each entry, resulting in a failure trend summary for future reference [14]. Similar ideas could be applied to organizing repairability design insights obtained from Amazon product reviews. The creation of a repairability taxonomy for a variety of consumer electronics could give product designers access to specific repair-relevant information with little required effort. With the addition of device-specific insights such as those presented in this research, product designers would be well equipped to design devices that last, helping to reduce their environmental impact.

2. METHODOLOGY

To examine if customer feedback from Amazon reviews can help designers obtain repairability-related design insights, a two-part approach was used. This approach included 1) evaluating a comprehensive range of repairability-related issues across a category of devices and 2) comparing specific models within that category. Standalone computer keyboards were selected as a case study to examine the efficacy of this approach. This method is split into three steps: 1) obtain repairability-related Amazon reviews for keyboards, 2) perform topic modeling using NMF and BERTopic to discover general trends, and 3) compare failure modes for three specific keyboards. Each step is explained in detail in the following sections.

3.1 Extract Repairability-Related Text Data

This research used Amazon product reviews for 10 standalone computer keyboards found under the search term "office keyboard". The researchers selected keyboards with a large number of reviews in order to capture a diverse range of customer experiences. Since reviews typically contain a mix of opinions (e.g., likes and dislikes), they were parsed into sentences for the analysis presented in the subsequent sections. To capture repairability-related reviews, a filtering process was needed to distinguish repair-relevant reviews from other customer comments. A repairability keyword list was developed for this purpose.

3.1.1 Method for Creating Repairability Keyword List

Developing the repairability keyword list involved an iterative process of brainstorming and refining. Initially, 500+ keywords were generated by reviewing Amazon articles and manually creating a list of words [9, 16]. Additional brainstorming to add to the list involved creating keywords for various categories related to repairability, such as tools, action verbs, and components related to repairing. Subsequently, the keyword list was refined by evaluating its performance in filtering repairability-related product reviews. This evaluation compared the automatically filtered results to manually sorted results. 2000 randomly selected reviews were scored manually by a primary coder based on whether they were related to repairability using the following criterion:

"Reviews are considered repairability-related if they include content about a keyboard failure mode or attempt at repair; this includes feedback about keyboard component malfunctions and physical damage but not feedback on undesirable design features."

For example, a repairability-related keyboard review is "keyboard needs to be unplugged and plugged back in after using laptop in order to function" because it describes a malfunction. On the other hand, an example of a non-repairability review is "I am very surprised to find it has no feet in the back to provide a proper tilt for typing" because the review is commenting on a perceived design flaw. Inter-rater reliability analysis was conducted by having a second coder independently sort 15% of the data with the provided criterion. The Cohen's Kappa was ran to determine that there was a sufficient agreement between the two coders' decisions, κ=0.76. After achieving this Cohen's Kappa, the keyword list was refined iteratively by examining how slight changes affected what was flagged as repairability-related. Once 12% of the 2000 test sentences were correctly flagged, the keyword list was accepted. This resulted in a list of 42 repairability keywords. Examples from the list include "disconnect", "screw", "troubleshoot", and "unresponsive." The complete list of keywords is available upon request from the authors.

3.2 Topic Modeling with NMF and BERTopic

To prepare the filtered sentences for topic modeling, a few additional steps were needed. First, sentiment analysis was performed to categorize sentences as either being positive or negative. Only the negative sentences were used for topic modeling.

Table 1. Keyboards Selected for Comparison.

<table>
<thead>
<tr>
<th>Keyboard Type</th>
<th>Model</th>
<th>Manufacturer</th>
<th>Price (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wired</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wireless</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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modeling to maintain focus on keyboard failure modes. For NMF, the filtered sentences were preprocessed using NLP modules in Python. This included removing stopwords and tokenization. The words “work” and “keyboard” were added to the stopwords list to reduce noise in the data due to their frequent usage in the reviews. This preprocessing was not needed for BERTopic because it uses the transformer model BERT to effectively process the original text data.

Topic modeling was performed using both NMF and BERTopic on the collection of repairability-related sentences. Review sentences from all 10 keyboards were considered to examine failure mode trends across devices and provide sufficient test data for topic modeling.

### 3.3 Evaluation of Repairability-Related Issues for Specific Devices

After topic modeling was performed to analyze general trends, these keyboards were studied individually to determine 1) if the sentence filtering method could be used to learn about the repairability of individual devices and 2) if this method could be used to compare device repairability.

Three keyboards of a similar price range were selected from the original group of 10 keyboards. Table 1 gives further details on the three keyboards selected for comparison.

To compare these models, the keyword list was used to extract repairability-related sentences from the collection of reviews for each keyboard. These three keyboards had 217, 219, and 162 repairability-related sentences used for comparison, respectively. The extracted sentences were then manually read and synthesized to determine common failure modes for each device. Note that topic modeling was not conducted for comparison analysis due to the limited number of reviews available for each individual device. Results are presented in the following section.

### 4. RESULTS AND DISCUSSION

#### 4.1 Topic Modeling Results for 10 Keyboards

For each of the 10 keyboards, 100 reviews were scraped for each star rating (i.e., 1-5-star ratings), resulting in 500 reviews for each product. This resulted in a total of 24,925 sentences.

<table>
<thead>
<tr>
<th>Table 2. Failure Mode Representative Topics from NMF and BERTopic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Failure Modes</strong></td>
</tr>
<tr>
<td><strong>Key</strong></td>
</tr>
<tr>
<td><strong>Keys sticking</strong></td>
</tr>
<tr>
<td><strong>Letters wearing off the keys</strong></td>
</tr>
<tr>
<td><strong>Codebook base legs</strong></td>
</tr>
<tr>
<td><strong>Keyboard legs breaking</strong></td>
</tr>
<tr>
<td><strong>Keyboard disconnecting</strong></td>
</tr>
<tr>
<td><strong>Bluetooth disconnecting</strong></td>
</tr>
<tr>
<td><strong>Mouse</strong></td>
</tr>
<tr>
<td><strong>Connect</strong></td>
</tr>
<tr>
<td><strong>Keyboard lagging</strong></td>
</tr>
<tr>
<td><strong>Need to unplug/ re-plug</strong></td>
</tr>
<tr>
<td><strong>Missing letters/ typing errors</strong></td>
</tr>
<tr>
<td><strong>Example</strong>: “I’m an experienced typist, but the sheer number of times I’ve had to stop to correct extra or missing letters is slowing me typing to a crawl”</td>
</tr>
</tbody>
</table>
Using the keyword list, 1,888 repairability-related sentences were extracted.

The results for both the NMF and BERTopic approaches are given in this section, as well as a comparison between them. For the NMF approach, a coherence score methodology was used to determine the best number of topics based on the input data. This resulted in 75 topics. For BERTopic, 15 topics were identified, where the number of topics was selected automatically. For both NMF and BERTopic, many of the identified topics indicate keyboard failure modes and repair needs. Selected NMF and BERTopic results that represent failure modes are given in Table 2. Most topics are represented by five words determined by the topic modeling methods (a few topics only have three or four words depending on the topic modeling result).

As shown, both NMF and BERTopic identified relevant repairability information and failure modes from the Amazon product reviews. For instance, both approaches identified problems with keys sticking, Bluetooth disconnecting, keyboard legs breaking, and unstable keyboard bases. This continuity gives confidence to the notion that topic modeling of Amazon product reviews can identify failure modes and provide leads for designers. For example, feedback about keyboard legs snapping off might inspire designers to improve keyboard leg durability and provide or sell replacements.

In addition to meaningful topics such as those given in Table 2, results from both NMF and BERTopic include topic redundancy and noise in the data. For NMF, examples of topics that show noise in the data include “year, site, break, wear, fix, no reason, cable, defect, wrong, ‘problem, fix, doesn’t, manufacture, search, appear, hope, care, amazon,” and “day, time, multiple, every, return, final, get, window.” Examples of duplicate topics from NMF include “constant, disconnect, bluetooth, wifi, unresponsive, require” and “connect, device, bluetooth, disconnect, issue, wireless, lost.” Both topics are about the keyboard’s Bluetooth disconnecting from the paired computer. While BERTopic generated fewer topics than NMF, there are still redundant topics and topics that do not represent failure modes. Examples of redundant topics include “bar, space, spacebar, stick, sticking,” and “bar, space, spacebar, started, sticking.” Both of these topics are about the spacebar sticking. Examples of topics that show noise in the data are “fix, troubleshooting, tried, fixed, problem,” “key, expensive, board, need, used,” and “sucks, can’t get, minor, purple.”

While repairability-related design insights can be obtained from both approaches, the approaches differ in performance. BERTopic resulted in more consolidated topics, with fewer duplicates and fewer topics without repair substance. On the other hand, NMF resulted in a greater number of unclustered topics, which matched previous performance with short text data [24].

The overall conclusion from this work is that repairability-related design insights can be derived from customer feedback. This methodology can be used by designers to improve the repairability and thus sustainability of their products. Additionally, there is room for future work to refine the application of topic modeling for this purpose.

### 4.2 Comparison Result for 3 Selected Keyboards

From manually evaluating different keyboards based on repairability-related sentences, keyboard-specific failure modes of these different devices were identified. Table 1 gives an overview of the three keyboards chosen for comparison. Results

<table>
<thead>
<tr>
<th>Failure Modes</th>
<th>Keyboard 1: Logitech Wired Keyboard</th>
<th>Keyboard 2: Arttec Wireless Keyboard</th>
<th>Keyboard 3: Amazon Basics Wired Keyboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keys sticking</td>
<td>“the keyboards are nice at first, then the keys get sticky and the letters rub off”</td>
<td>“after cleaning the keyboard there were a few that were sticking”</td>
<td>“after about a year of use, the spacebar started to stick”</td>
</tr>
<tr>
<td>Letters wearing off the keys</td>
<td>“the white paint they use to print the letters on the keys wear off on certain keys faster than others although the keyboards still work fine”</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Wobbly keyboard base</td>
<td>X</td>
<td>X</td>
<td>“wobbles when type and can’t be adjusted”</td>
</tr>
<tr>
<td>Keyboard legs breaking</td>
<td>“still legs break easily”</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Bluetooth disconnecting</td>
<td>X</td>
<td>X</td>
<td>“disconnects even though wired in”</td>
</tr>
<tr>
<td>Keyboard lagging</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Need to unplug/re-plug</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Missing letters/typing errors</td>
<td>X</td>
<td>X</td>
<td>“I thought at first it was just my typing but after using it for a few days and letting the battery get lower I noticed that if I let it get really low it was missing 1/2 the keys I pressed and I’d really have to push down on the buttons to get them to respond.”</td>
</tr>
</tbody>
</table>
for the failure mode comparison, including examples from customer reviews, are given in Table 3.

These results qualitatively show the repairability-related insights that can be obtained from customer feedback. While this evaluation does not present information on the magnitude of these issues, it is still useful to know the failure modes present for each device. Many of the same failure modes were present across devices and match the trends uncovered from topic modeling. For instance, all three keyboards had issues with sticky keys, and two of them had issues disconnecting from the paired computer. Unique issues were also picked up through this process, including letters wearing off keyboard #1 and keyboard #2 rubbing on the desk. These keyboard-specific findings indicate the potential for future work that uses customer feedback to improve repairability of various electronic devices.

4.3 Applications

There are two main applications for repairability-related insights derived from customer feedback. First, as mentioned, this methodology could be used in the design process. In early product design and development stages, product designers could employ this approach to learn about common repair concerns for devices already on the market. In doing this, they would learn aspects of their product where durability should be a priority, which components are repair-critical (to ensure easy-access and modularity), and which components to make available as replacement parts. Product designers could also use this approach to make improvements to their own existing products that have already received customer reviews.

The second potential application is for consumers. Repair-conscious consumers have the power to drive change by supporting the companies trying to change the disposable electronics paradigm. For consumers selecting a product with repairability in mind, a way to compare the repairability of different products based on customer feedback would be useful. While expert repairability scores (such as those from iFixit) reflect in-depth teardowns and design for repairability analysis, they do not necessarily predict the failure modes of a device based on real, long-term usage. Additionally, expert repairability scores are not available for all devices. For a consumer-facing platform, the methodology proposed here and future work automating a repairability comparison tool would likely need a user-friendly interface and web-accessibility.

5. LIMITATIONS AND FUTURE WORK

There are several limitations to this research and areas that warrant continued research and development. The first limitation is the performance of the keyword list for repairability-related sentence filtering. Additional methods for list refinement should be explored and tested with the goal of achieving a sorting accuracy above 80%. A second limitation is the quality of the topic modeling results. While still largely useful for deriving repairability-related design leads, the topics were sometimes unclear and unconsolidated. Improvements to the topic modeling approach would be useful for future development of this work as a design tool.

Other next steps in this research include applying it to other products of varying complexity and mechanical functionality (i.e., laptops or washing machines). It may also be useful to explore classifying failure modes as electrical or mechanical failures. Additionally, test data from online repair forums or expert reviews and performance tests could be used for topic modeling. This would allow comparison between the repairability design insights from these sources and the insights derived from customer feedback.

To ensure this process can be easily implemented, it would be useful to transform the device repairability comparison from a manual to an automated process and make it more quantitative. There is also an opportunity to transform the topic modeling approach into a more user-accessible design tool and/or consumer reference.

Additionally, integrating qualitative repairability design leads with quantitative sustainable design metrics early in the product design process could magnify the environmental benefit. For instance, repairability design leads could be used with circular economy indicators to quantify the product circularity benefit from enhanced repairability [35]. Repairability design leads could also be coupled with other quantitative and qualitative sustainable design methods, such as the approach in [36] that focuses on improving end-of-use product value recovery.

6. CONCLUSION

This research presents a method for extracting repairability-related insights, explores design insights derived from topic modeling, compares topic modeling approaches, and applies this thinking to compare three specific Amazon keyboards. The future directions for this work are exciting in their potential to improve design for repairability in consumer products. In turn, repairable products help keep e-waste out of landfills and reduce greenhouse gas emissions, both of which are necessary societal adjustments during the climate crisis.

7. REFERENCES


# APPENDIX C. BAMBU LAB P1S TECHNICAL SPECIFICATIONS

## Bambu Lab P1S

### Technical Specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Printing Technology</strong></td>
<td>Fused Deposition Modeling</td>
</tr>
<tr>
<td><strong>Body</strong></td>
<td></td>
</tr>
<tr>
<td>Build Volume (W x D x H)</td>
<td>256 x 256 x 256 mm³</td>
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<tr>
<td>Chassis</td>
<td>Steel</td>
</tr>
<tr>
<td>Shell</td>
<td>Plastic &amp; Glass</td>
</tr>
<tr>
<td>Hot End</td>
<td>All-Metal</td>
</tr>
<tr>
<td>Extruder Gears</td>
<td>Steel</td>
</tr>
<tr>
<td>Nozzle</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Max Hot End Temperature</td>
<td>300°C</td>
</tr>
<tr>
<td>Nozzle Diameter (Included)</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Nozzle Diameter (Optional)</td>
<td>0.2 mm, 0.6 mm, 0.8 mm</td>
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<tr>
<td>Filament Cutter</td>
<td>Yes</td>
</tr>
<tr>
<td>Filament Diameter</td>
<td>1.75 mm</td>
</tr>
<tr>
<td><strong>Toolhead</strong></td>
<td></td>
</tr>
<tr>
<td>Build Plate (Included)</td>
<td>Bambu Dual-Sided Textured PEI Plate</td>
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<tr>
<td>Build Plate (Optional)</td>
<td>Bambu Cool Plate, Bambu Engineering Plate, Bambu High Temperature Plate</td>
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<tr>
<td>Max Build Plate Temperature</td>
<td>100°C</td>
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<tr>
<td>Max Speed of Toolhead</td>
<td>500 mm/s</td>
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<tr>
<td>Max Acceleration of Toolhead</td>
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<td>Max Hot End Flow</td>
<td>32 mm³/s @ABS(Model: 150x150mm single wall; Material: Bambu ABS, Temperature: 240°C)</td>
</tr>
<tr>
<td><strong>Cooling &amp; Filtration</strong></td>
<td></td>
</tr>
<tr>
<td>Part Cooling Fan</td>
<td>Closed Loop Control</td>
</tr>
<tr>
<td>Hot End Fan</td>
<td>Closed Loop Control</td>
</tr>
<tr>
<td>Control Board Fan</td>
<td>Closed Loop Control</td>
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<td>Chamber Temperature Regulator Fan</td>
<td>Closed Loop Control</td>
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<tr>
<td>Auxiliary Part Cooling Fan</td>
<td>Closed Loop Control</td>
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<tr>
<td>Air Filter</td>
<td>Activated Carbon Filter</td>
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<td><strong>Supported Filament</strong></td>
<td></td>
</tr>
<tr>
<td>PLA, PETG, TPU, ABS, ASA, PVA, PET</td>
<td>Ideal</td>
</tr>
<tr>
<td>PA, PC</td>
<td>Capable</td>
</tr>
<tr>
<td>Carbon/Glass Fiber Reinforced Polymer</td>
<td>Not Recommended</td>
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<td><strong>Sensors</strong></td>
<td></td>
</tr>
<tr>
<td>Chamber Monitoring Camera</td>
<td>Low Rate Camera 1280 x 720/0.5fps Time-lapse Supported</td>
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<td>Filament Odorometry</td>
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<td>Power Loss Recover</td>
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<tr>
<td>Dimensions (WxDxH)</td>
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<td>Net Weight</td>
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<td><strong>Electrical Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Input Voltage</td>
<td>100-140 VAC, 50/60 Hz</td>
</tr>
<tr>
<td>Max Power</td>
<td>1000 W @220 V, 350W @110V</td>
</tr>
<tr>
<td>USB Output Power</td>
<td>5V/1.5A</td>
</tr>
<tr>
<td><strong>Electronics</strong></td>
<td></td>
</tr>
<tr>
<td>Display</td>
<td>2.7-inch 192×64 Screen</td>
</tr>
<tr>
<td>Connectivity</td>
<td>Wi-Fi, Bluetooth, Bambu-USB</td>
</tr>
<tr>
<td>Storage</td>
<td>Micro SD Card</td>
</tr>
<tr>
<td>Control Interface</td>
<td>Button, APP, PG Application</td>
</tr>
<tr>
<td>Motion Controller</td>
<td>Dual-Core Cortex M4</td>
</tr>
<tr>
<td><strong>Software</strong></td>
<td></td>
</tr>
<tr>
<td>Slicer</td>
<td>Bambu Studio, Support third party slicers which export standard G-code, such as Cura, but certain advanced features may not be supported.</td>
</tr>
<tr>
<td>Slicer Supported OS</td>
<td>MacOS, Windows</td>
</tr>
</tbody>
</table>
APPENDIX D. IDEATION SKETCHES

4/5/24 - IDEAS FOR KEYCAP/PLUNGER INTEGRATION

PROBLEM:
1) NEED A WAY TO 3D PRINT REPLACEMENT KEYPADS + TOP HOMING OF PLUNGER KEYPAD - NEED PRINCIPLE + SIMPLE DESIGN.
2) PEOPLE OFTEN COMPLAIN ABOUT "MUSHY" FEEL OF PLUNGER KEYPADS - WOULD BE NICE TO IMPROVE TYPING EXPERIENCE.

POSSIBLE SOLUTIONS:
WOULD BE IDEAL TO USE KEYBOARD SWITCHES (STANDARD, OTS COMPONENTS) AND ADAPT THEM TO FIT PLUNGER KEYPAD. (THEY ALREADY HAVE SPRING & METAL KEYCAPS)

EXTERNAL TOP CLEAR HOMING OF KEYPAD WOULD SNAP FIT INTO TOP HOUSING PLATE

GREEN MOVING PIECE
RIGID IN PLACE

NEED TO CONNECT SPRING SHAFT TO UNPRESSED PLUNGER!

TWO IDEAS TO TEST

1) 3D PRINTED PRESS ATTACHMENT TO INCREASE SHAFT CONTACT W/ PLUNGER TO LOWER STICKYNESS

OR

SECOND RISE OF TOP AT PLUNGER

CIRCULAR EXERCISATION TO LEAVE SMOOTH SHOT
First idea - simpler of the two for design, manufacturing, and assembly.

Top Plate

This is a way to locate keycaps on plungers. Could go with this idea? Won't work. Need a spring there!

Attachment to increase contact area.

Base Plate idea. Extend movie plunger to have enough height to support spring. Supports for base to get correct height. Won't work. No room for spring.

Base plate idea. Extend movie plunger to have enough height to support spring. Supports for base to get correct height. Won't work. No room for spring.

Plunger layer

Need first attempt to hold top of switch in place. Must fit into holes. Extrusion height as integrated.

For first test:

Small square to test keycaps. Design for support on support.

Could cut springs in 1/2!
APPENDIX E. CAL POLY NEWS ARTICLE

CAL POLY NEWS (/NEWS)

BROWSE CATEGORIES

DIVERSITY, EQUITY AND INCLUSION (/NEWS/CATEGORY/DIVERSITY-EQUITY-AND-INCLUSION)

CALIFORNIA IMPACT (/NEWS/CATEGORY/CALIFORNIA-IMPACT)

SHARE A STORY IDEA (/FORM/SHARE-STORY-IDEA)

CALIFORNIA IMPACT

Engineers Embrace Repair Culture as New Law Takes Shape in California

WRITTEN BY ROBYN KONTRA TANNER // PHOTOS BY DYLAN HEAD | MAY 5, 2024
Last fall, California passed SB 244, otherwise known as the Right to Repair law, which requires tech manufacturers in the state to provide tools, parts and documents that consumers or repair shops need to service or fix devices.

Though the legislation doesn’t go into effect until July, Cal Poly engineers have already embraced repairability to help cut down on e-waste and improve sustainability.

Mechanical engineering student Claire Franz is studying why consumers dispose of membrane computer keyboards instead of repairing them. Franz, who is earning her bachelor’s and master’s degrees concurrently, felt inspired to tackle this concept in her master’s thesis after an internship with iFixit, a repair expertise hub for consumer electronics founded by Cal Poly alumni.

Franz and professor Hyeonik Song identified the most common user complaints by using natural language processing to analyze 5,000 Amazon reviews across 10 common brands.

Then Franz took the most common complaints — like dead or sticking keys — and developed physical solutions using 3-D printed components. The goal of the project was to shift the design thinking framework from prioritizing efficient manufacturing to prioritizing repairability.

“Design for manufacturing aims to optimize product designs for efficient and cost-effective manufacturing processes, so it has more direct impact on designers, engineers and manufacturers,” Song said.

“Design for repairability prioritizes the durability and reusability of a product, which directly impacts the users and the environment.”

When Franz first brought the idea to Song, he was intrigued — previously, his research focused on product performance and quality. He also hadn’t examined whether consumer opinions could be incorporated in the early design phase before.

“Now, my research question is, ‘How can we help designers be more creative while focusing on sustainability early in the process?’” said Song. “It was a life-changing moment to meet a student like Claire.”
The team has coauthored a conference paper on the study that they will present at the International Design Engineering Technical Conference in Washington, D.C., in August.

But Franz and Song aren’t the only engineers working toward sustainability. The Repair Café (https://polyrepair.net/), founded by mechanical engineering student Quinn Horak, is a student club that invites community members to bring broken appliances, bikes and other items to regular events on campus for a free fix. The goal is to reduce unnecessary waste and sharpen repair skills for club members while helping the community.

“Consumers should not be beholden to companies for the privilege of fixing goods they’ve already paid for,” said Horak. “The environmental benefits of reusing and repairing items are also significant. Every time we repair instead of replace, we eliminate all emissions associated with producing and shipping a new product to consumers.”

The Repair Café has partnered with the Cal Poly Amateur Radio Club to host three events in 2024 (https://ceng.calpoly.edu/connection/2023/10/the-fix-is-in-repair-cafe-comes-to-cal-poly/), with more on the way. Horak says he’s excited about the potential for California’s new law to drive down the cost of repairing versus buying new.

“By allowing individuals and independent repair shops access to the same documentation and parts as their corporate counterparts, a more robust and competitive service economy is formed,” he said. “Besides creating jobs and reducing repair costs, this also makes repair a more compelling alternative to replacement.”

California isn’t the only state with a Right to Repair law on the books — other states have recently enacted similar laws — but Song says California’s repair culture could be a tipping point for the industry.

“California currently houses major consumer electronics companies and therefore holds a crucial role in this context,” said Song. “As these companies actively embrace the repair movement, other companies worldwide could be motivated to follow the trend.”