Sustainable Model for Design

A Major Qualifying Project Report

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Introduction

In the United States, 1 in 4 adults is affected by arthritis, the inflammation or swelling of joints. There are many types of arthritis, with the most common symptoms being pain and immobility in joints. According to the Centers for Disease Control and Prevention (CDC), osteoarthritis, rheumatoid arthritis, gout, fibromyalgia, lupus, and childhood arthritis are the six most common forms of arthritis (CDC, 2021). It is a disability that is more prevalent in older adults. For example, the age group of 45-64 makes up 30.7% of those with arthritis (CDC, 2021). Due to the demographic shift and an aging population, and it is estimated that by the year 2040, 26% of US adults will be diagnosed with arthritis (CDC, 2021). Those with the disease cannot do many simple daily tasks.

There are products that can help people living with arthritis. Such ‘assistive devices’ help ease the pain and allow people to be more independent. Such devices help arthritis sufferers by reducing the effort needed to perform functions, leveraging strength, reducing the movement required. Examples of assistive devices include extended handle tools, spring-loaded scissors, and electric toothbrushes. These devices have larger handles, automatic movements, easy-to-grip, or easy trigger levers.

Around 8.5% of the worldwide population (617 million) are aged 65 and over (NIH, 2016). Also, the population is projected to be 1.6 billion by 2050 (a 17% increase) (NIH, 2016). Given the aging population in the US, the market for assistive devices is bound to grow in the coming years. In 2018, the global elderly and disabled assistive devices market was worth $23 billion (Joshi, 2019). There is a *compound annual growth rate*, *(*CAGR), a measurement of the annual growth rate of an investment value over time, of 5.5% from 2019 to 2026 (Joshi, 2019). Since arthritis is more prevalent in the older group, the demand for assistive devices will also increase, and so will their production.

Yet many products are usually made from cheap non-recyclable plastic, or are of poor quality, causing them to break easily and end up in landfills. Despite this, the environmental impact of this increased production is largely ignored. Currently, there is an increase in consumer demand for sustainable products. Based on a study by Simon-Kucher & Partners conducted in July 2021, when consulting more than 10,000 people from across 17 countries, they recognized a shift of positive attitude toward consuming sustainably. Globally, 85% shifted to be more sustainably conscious, while 61% of people see sustainability as a criterion for purchase, and 34% are willing to pay extra for those products (Business Wire, 2021). Despite the given demand for sustainable products, producers of these devices are still not taking the environmental impacts of their products seriously. Given the environmental imperative to reduce waste, and the consumer readiness to seek out sustainable products, designers must take into account an increased demand for greener products and design them with the consumer criterion in mind.

This project responds to the need to meet the demand of a growing market for assistive devices in a less wasteful, more sustainable way. I do this by developing a model to design sustainable products and look at what aspects should be considered. Then I apply the model to the case of the 'Frannie', a crocheting device that assists arthritis sufferers to relieve the pain of crocheting. Frannie is mainly in the designing stage and a prototype has been made by a 3D printer using PLA plastic that makes up the entirety of the device.

The concepts to create a sustainable design model

Introduction

There are many sustainable concepts to design a sustainable product, and they can be overwhelming and unmanageable. Having a framework streamlines the process of sustainable design by organizing the relevant concepts so that at each phase the designer can consider potential steps to reduce waste, replace parts (instead of the whole device), and other ways to make the product more sustainable. This model visualizes the possible ways to have a product last as long as possible, and an example could be what materials to consider. The framework is based on two well-known processes: the LCA and CE. Each of these offers a different perspective on sustainability and bringing elements from each to the development of a new model can help create a more comprehensive framework. Using these concepts, a new framework will be built to incorporate those ideas and apply them to develop a sustainable assistive device.

Life cycle analysis

Life cycle analysis (LCA) is the analysis of the potential environmental impacts of a product during its entire life cycle (Sphera, 2020). The most common assessment is "cradle to grave," which is a linear model where there exists an End of Life (EoL). LCA is a tool to compare environmental impacts or assess how industrial activity interacts with the environment (Pucylowski, 2017).

There are four major phases in performing a life cycle analysis by an analyst. These are 1) goals and scope definitions, 2) life cycle inventory analysis (LCI), 3) life cycle impact assessment (LCIA), and 4) interpretation (RIT, 2020). These are the general form of how LCA is performed by a professional, and examples will be given later on.

First, the goal and scope must be defined and have limitations to outline where to start or end. Since there are so many potential impacts, it will require a substantial amount of time or knowledge. For example, just one stage of extraction of materials like corn for bioplastic will include the energy intake to harvest the materials, transportation, the emissions coming from the action of extraction, the agricultural impacts like the chemical that might be sprayed on, and all of that must be measured and calculate for all the corn that was harvested. One approach is to narrow LCA in scope by having a focus on one point or one impact category to make it more manageable (RIT, 2020).

Another approach is having a more comprehensive overview of the entire life cycle, including many impact categories (RIT, 2020). Examples of impact categories are contributing to climate change, energy demand or loss, air pollution, or water use (RIT, 2020). These categories are the focus that is relevant to the goal; let's say if the goal is to reduce the overall air pollution for cars, then the professional will primarily focus on the data on air pollution rather than other data like water use.

The second phase is the life cycle inventory analysis; This is the data collecting stage where the industrial system's input (e.g., energy) and output (e.g., emissions) are measured (RIT, 2020). This is an inventory of data where all the measurement quantities like volume, mass, or weight are collected, for example, measuring the quantity of energy used or material used for the raw material extraction stage of cement (RIT, 2020).

The third phase is analyzing the data collected, and it is called life cycle impact assessment; From those recorded measurements, this is where the analyst determines the broader human/environmental impacts; essentially putting meanings into the data (RIT, 2020). Let's say that a manufacturing process contributes around 10 tons of CO_2; the analyst will translate this number so that the people understand the damages/impacts that those 10 tons can make (RIT, 2020). Another example is the amount of water used to mine lithium as that not only contributes to vast amounts of water use but the contamination as well, so analysts can express how it will cause more than one issue. Also, this is the phase that answers the goal or determines the core of the issue that needs to be looked at for future cases.

Lastly is the interpretation phase, which is where the analyst concludes the result from the performed LCA and it is ready to be used. The conclusion from this phase provides recommendations for future improvement or alternative options. The diagram below will showcase an example of an end result of the LCA process with the input and output of each stage of manufacturing. The diagram is an example of what might be presented to the producers or the consumers to understand the input and output of each stage of manufacturing.

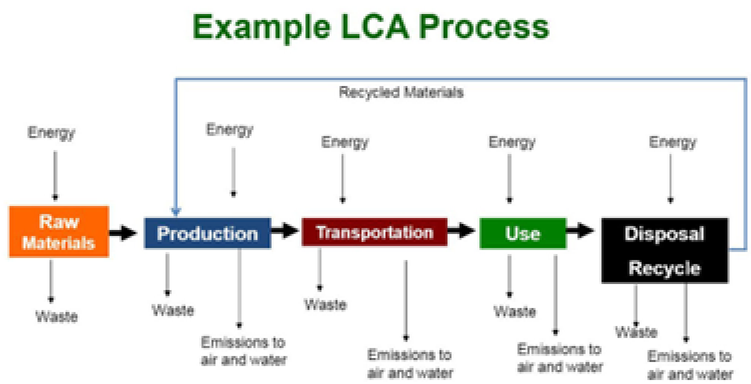

Figure 1*: LCA process* (Pucylowski, 2017)

To understand LCA as an application, one example is a study performing LCA on a polymer plastic material called Polylactic Acid (PLA). There are four points of the life cycle of PLA that contribute to energy emission and they are: ((1) gathering raw material and its conversion into usable PLA, (2) processing into the desired shape of products (3) use, and (4) End of Life (EoL) (Rezvani, 2021). Through LCA, we can understand this life cycle and PLA's impact. Noting that this is one specific case of LCA, the goal is to only focus on the four points of the PLA life cycle, more specifically their energy intake and loss. The steps of this life cycle are specific to this one material. The steps described here are gathered from the inventory of previously collected data, and they are now describing the meaning of those data.

Following the four phases described above,

1. The goal of this example is to find the impact the of PLA on emissions and energy intake

2. Inventory analysis: previously collected data like literature reviews, electricity use/emissions/etc.

3. Impact assessment: The first point, gathering raw materials and its conversion into usable PLA, has the greatest impact/most harmful

4. Interpretation: The first point has the largest emission and recommendations are given.

The four stages of the PLA life cycle that will be discussed are an example of inventory analysis and the type of data that are collected. The first stage (feedstock collection and its conversion) in the life of PLA is turning raw material into the PLA, making 1 kg of PLA using corn; in terms of energy intake, natural gas and electricity take up most of the energy used (Rezvani, 2021). The entire process emits around 2.8 kg CO_2/kg PLA (Rezvani, 2021).

The second (processing) is the manufacturing method, and one of the standard methods is injection molding which uses around 7.2 MJ/kg of electricity for 1 kg of PLA (Rezvani, 2021). The third is using PLA in products, and depending on what it is used for, it has its input and output (Rezvani, 2021). Lastly is the EoL, and one example of emission is the total GHE of PLA landfill (without biodegradation) release of around 1.2 - 0.9 kg of CO_2 per kg; with biodegradation, it can be much more (Rezvani, 2021).

The study concluded that the first stage takes up around 50% of total emission, making it the 'hotspot' (the stage with the most amount of impact) (Rezvani, 2021); the largest negative climate impact and negative influence on human health. So if there is one point that was known to contribute more than the rest of the point of PLA life then this point should be put more focus. This part is phase 4, which is the interpretation of the LCA performed for us to understand that there is a specific stage that emits the most emission and it should be further improved. While this case study does not discuss the third phase more in detail, which is impact assessment in terms of broader impact, it highlights the large amount of emission that one stage of the PLA life cycle can emit.

Circular economy

Another type of concept is "cradle to cradle," which is a circular economy model, where a product's end of life directly goes into another cycle, often by having a recovery process (RIT, 2020). Many industries followed a linear system, which means they were discarded once the products reached their end. However, circular economy does not have an end of life rather there is a recovery process, where we are taking those products and returning them to the life cycle, production, and use. The end goal of having a circular economy is based on three principles: reducing waste, circulating products and materials, and regenerating nature which are all driven by design (Ellen MacArthur Foundation, "Circular economy overview").

The first principle of reducing waste and pollution is simply shifting away from the linear systems and moving away from single-use products. One example is having edible food packing or having no packaging at all to take away the single-use component of the product. Straw is another example as plastic straw can only be used once but if the cup is designed to allow sipping then there is no need for a straw. The second principle is to keep the product in use by having it last longer, be transferred to a new owner, and designed it so that it can be able to return back to the system; this process can be seen in the figure below. The last principle is after applying the two principles due to the fewer extraction of raw materials with this in mind, you can create the design with fewer raw materials thus it can leave space for nature to thrive.

The circular economy system uses processes like reuse, recycling, or remanufacturing to prolong the life of a product and minimize waste. The process allows for the product to be maintained or have the entire product or parts be reused in any of the stages in the life cycle. For example, the concept of reselling can enable reuse and therefore allow the product to still be in use. If it cannot be in use the parts can still be remanufactured and if they cannot be manufactured again they can be recycled. So it is incorporating the recovery process so that the product will not pass the end of life so that it is "cradle to cradle".

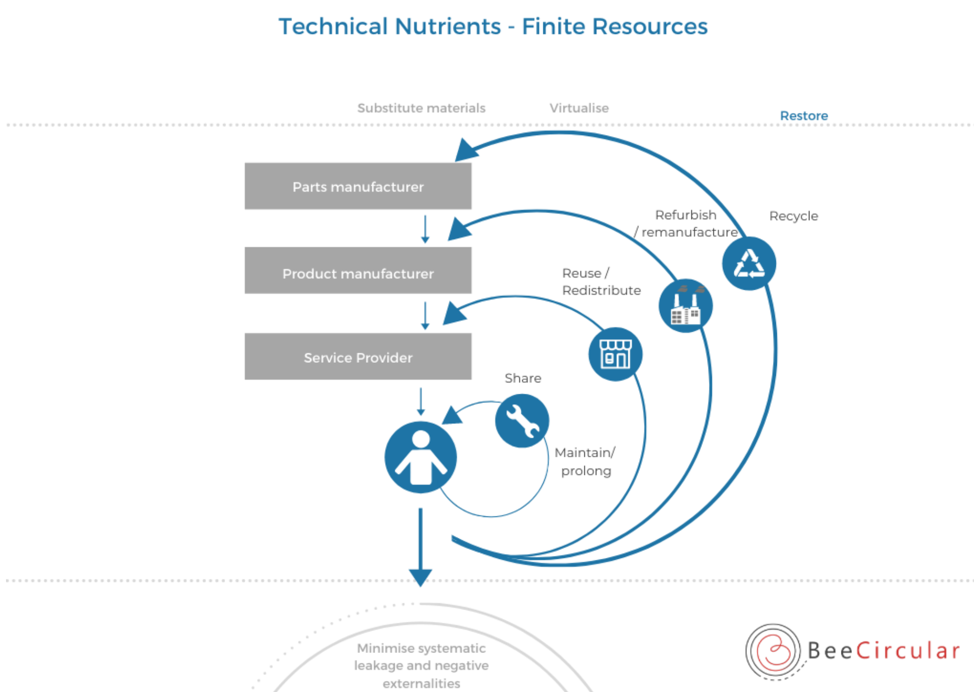

Figure 2*: Circular Economy Model* (Costa, 2017)

One example of applying this system is the clothing brand Napapijri, whose jacket is mainly manufactured with a recyclable polymer called Nylon 6. When the coat reaches its "end of life," it is chemically recycled into different nylon called Econyl, which can be made into a new piece of clothing (Ellen MacArthur Foundation, "Napapijri"). This is designed so that it can be able to be recycled and its recycled product can be used in another product so the product never really "dies". It is a concept in which we are facing away from the dependency on constantly creating new products and using the world's scarce raw materials (Ellen MacArthur Foundation, "Circular economy overview").

Goal and Objectives:

This project aims to support the reduction of the potential environmental impact of the growing market in assistive devices by creating and applying a framework for sustainable design, and then applying this framework to the case of ‘Frannie’, an assistive crocheting device aimed at arthritis sufferers.

Objective 1: integrate elements from both the well-known approaches to sustainability - LCA and CE – to develop a model of sustainable design, and apply this model to a case study.

Objective 2: determine the most relevant aspects of the model to Frannie, and apply them to Frannie

Results and Analysis

Objective 1: Develop a Model of Sustainable Design

Elements from the LCA and CE frameworks: The Framework of Sustainable Design

Sustainable Model for Design

In order to create guidelines on a framework to understand and enact the various points at which device sustainability can be affected, we need to integrate the concepts and ideas of LCA and circular economy. This is a new framework I call The Sustainable Model for Design.

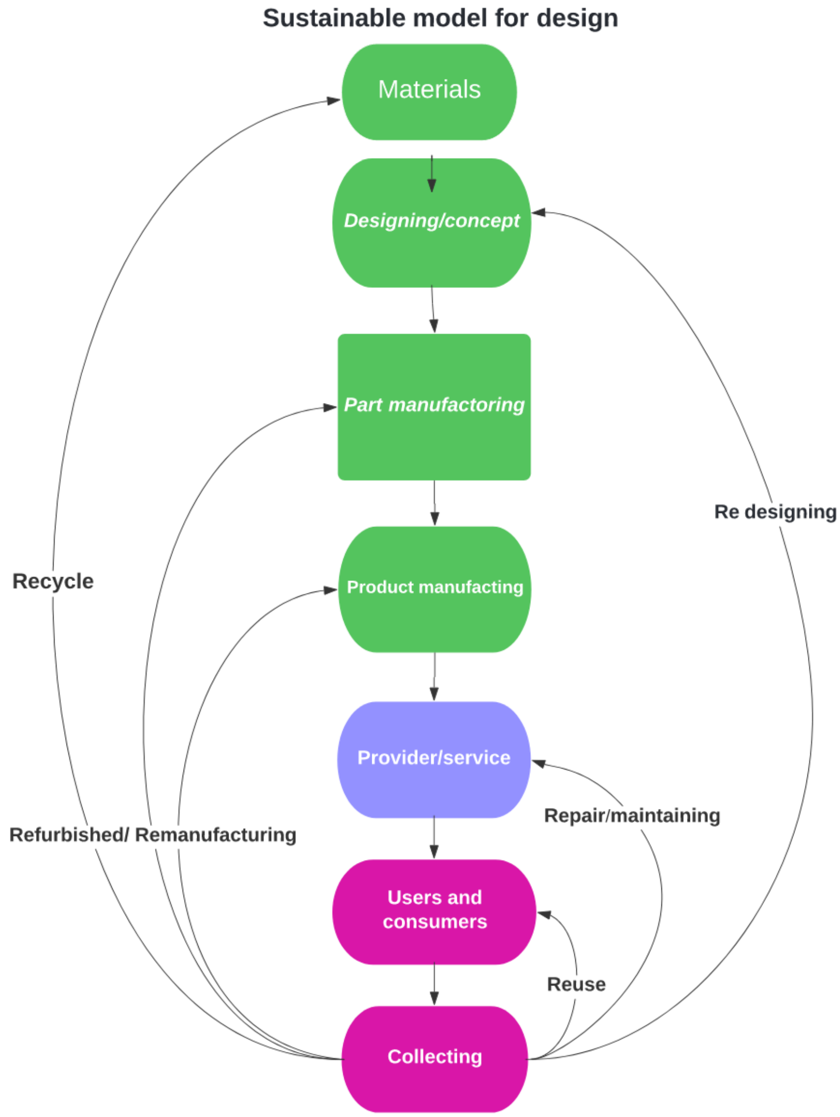

Figure 3

The diagram demonstrates a framework of the sustainability model, going from the prototype stage down to consumption. The model starts from understanding the process of extraction of materials and then when it goes past the usage stage it is collected to be reversed back into the system. Starting with raw material, the potential emissions and the energy input for the extraction or use of the material are acknowledged to understand the possible impacts of each material. Designing is the most important step where to have all the concepts be possible. It all depends on this stage. Eventually, when the product can no longer be in the life cycle since it is no longer usable there are processes of recovery to put the products back in the system. The first process is reuse which is to have the product be durable and last a long time, material is critical for this stage. Secondly, the repair is a process of having malfunctioning products go back to the companies that produce them, and can be repaired; This is a way of maintaining the functionality and prolonging their use. This can go the same with remanufacturing and refurbishing; they are similar in their ideologies. If the product cannot be able to go through the previous process it then can be recycled. Products that are properly recycled can be brought back into the product manufacturing or part manufacturing, and they then can reproduce, or their materials can be used in different products. Redesigning is a rethinking process where all the previous ideologies are incorporated to improve the product's sustainability. It is essential to be aware of the phases of the products so that the designers or manufacturers can make the concepts in the chapter possible. So, in this section, I will talk about the ideas in this framework in greater detail and incorporate examples of past studies to understand it better.

Material

Finding the most suitable material is imperative in creating a truly sustainable and long-lasting product. The most common materials for assistive devices are plastic, metal, rubber, ceramic, and paper (Raising Edmonton, 2021). Plastic is the most common material in single-use products; it is desirable due to being low cost, convenience of processing, and disposable (Gibbens, 2021). However, producing it requires fossil fuels, and once it is disposed of, it ends up in a landfill or breaks down into microplastic that mixes into the water and air (Gibbens, 2021). So despite being the ideal materials, the outcomes are far from "ideal".

There are, however, plastic alternatives such as bioplastic since it is made from plant-based materials and can be biodegradable. Two common bioplastics are PLA and PHA; PLA is especially beneficial since they are used in 3D printing and personal protective equipment (Tech Briefs, 2021). One example of recyclable plastics is PET(found in bottles), which can be turned into textile or construction materials (Ferrario, 2021). Another is HDPE, which is the easiest to recycle; it can also be downcycled into durable plastic products (Ferrario, 2021). For durability and reusability, metal is a fitting choice due to its strength and can be easily cleaned; some examples are aluminum and stainless steel (Williams, 2021). To extend the product's life and durability, materials like carbon fiber and stainless steel do not degrade throughout time or usage; their life could be extended for more than ten years (Mann, 2018). Materials are essential to ensure that the products can be recyclable or in a closed-loop system; therefore, it is necessary to design with suitable materials.

Repair/Refurbishing/Remanufacturing

Repair

To repair a product is to rework or replace only damaged parts without aiming to completely restore the product to the original specification (Eze, 2020). While it is similar to refurbish, where both aim to improve the products to prolong their use. The differences in the quality, repair does not strive to be identical to the original only to fix, whereas refurbishing tries to obtain original quality. For products to be more accessible for repair, they need to be modularity. Modularity is where a product can be easily disassembled into several components and assembled back together once corrected (Mann, 2018).

To further enable repair is to have the right to repair, which is giving direction for users to fix the product themselves. This is a concept that gives the users more access to repair their product without consulting a professional. This can be achieved by providing more information, parts, and tools, or just simply designing the product to be easier to repair by anyone (Khlosowski, 2021). Some manufacturers make their products to be unable to be repaired easily causing the user to buy a service or purchase a brand new product. Also having to go to get the product to be repaired will be costly. So encouraging the right to repair through laws can prevent the manufacturer from causing difficulty repairing (Khlosowski, 2021).

Some brands offer repair kits, have repair facilities in-store, and provide extra replaceable components (Khowala, 2018). There are many ways to have a product be easier to repair but it is important to design with the intent of repair like design for dissembling.

Refurbishing

Refurbishing is similar to remanufacturing and repair; retrieving the end-of-life products the difference is that refurbished products may have a lower quality standard and shorter warranty than the original (G.M, 2017). Examples of refurbishing a product are parts replacement or improving the overall quality. An example of manufacturers who have refurbishing systems is Siemens, Philips, and GE, which have implemented a system to collect their products to be refurbished. They also have facilities that specialize in this, and they sell their refurbished products with a full warranty under their names (G.M, 2017). This same concept could be applied to more simple tools, by providing spare parts, etc. Also, in terms of cost, it can sell for 60-70% of the original price (G.M, 2017).

Remanufacturing

An obsolete or close to an outdated product can be retrieved to be put back in service through remanufacturing. Remanufacturing primarily uses the whole product and is brought up a similar quality or better than the originals (Eze, 2020). Remanufacturing a product can be labor-intensive, but it requires less technological comprehensiveness than traditional manufacturing. For countries that are weaker economically, it could greatly benefit them due to added jobs, increased availability, and cheap costs. The average price of remanufactured products is 30% less than new products and 15% less energy for remanufacturing than new production of products (Eze, 2020). There is a lot to gain by using this approach, and it is an example of an aspect of a circular economy.

As seen below in the diagram of remanufacturing a product can go through around 9 steps of recovery so it regains its like-new condition. It goes through the process from disassembly to testing and then can be returns to be sell or back in service, and once it is no longer in use it can return to go through another process. One example highlighting the benefit of remanufacturing is a study conducted by the University of Michigan where they examined remanufacturing versus producing a new mid-sized gas-powered car engine. They found that remanufacturing requires 68-83% less energy and emits 73-87 % less carbon dioxide (RIT, "what is remanufacturing"). So remanufacturing opens up more opportunities for the product to be able to use again and sold again so it benefits both the environment and economically.

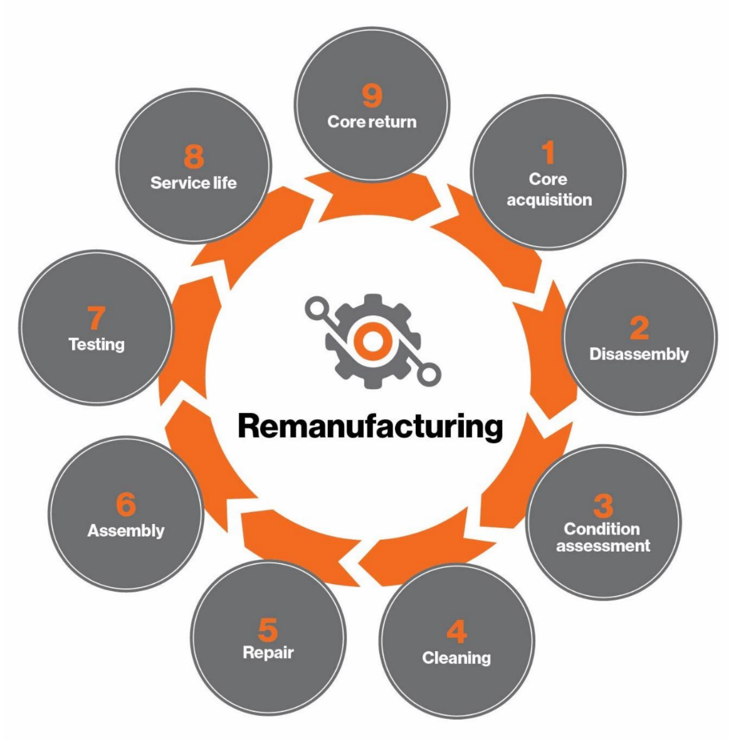

Figure 4: *Remanufacturing Diagram* (RIT, "what is remanufacturing")

Recycle

Recycling is collecting processed products and manufacturing them into something new (EPA, "how do I recycle"). The main reason for recycling is to limit energy use to harvest raw material and to limit overall waste. For the US, the recycling system starts with the collection, process, and manufacturing. The first step is to collect the product that can be recycled as there are limitations on what material can be recyclable (EPA, "how do I recycle"). Examples of materials that can be recycled are paper, plastic, glass, and metal (EPA, "how do I recycle").

However, most products, if contaminated, mixed with other chemicals or have food remnants, cannot be recycled and the common mistake is mixing plastic (rts, 2020). There are types of plastic that cannot be recycled (eg. straw) and due to temperature sensitivity material like thermoset plastic cannot be recycled at all (rts, 2020). Recycling is also not one-size-fits-all as depending on the resources or facilities, different areas have limitations on what they can collect or process (EPA, "how do I recycle"). Since after collecting the products they also must be sorted in the facilities to be processed and contamination or products that cannot be recycled can damage the resources, and are also costly to have it be sent out to landfills.

For recycling processing, the most common type is mechanical recycling, where it can be mechanically alters without changing its chemical structure (SL Recycling, 2020). Some of the steps include packaging (eg. grinding or milling), washing and drying, and pellet (eg. extrusion and cooling), then the pellet can be turned back into raw material (SL Recycling, 2020). Other types include energy recycling (converting to energy) and chemical recycling (modifying the chemical structures) (SL Recycling, 2020).

Recycling seems to be a sustainable choice to limit the waste of products however the system is flawed. The first problem is the contamination of products as it is not properly sorted or placed in the correct bin (Cho, 2020). One example is that if plastic is placed with cardboard then it is likely to be rejected and be placed in a landfill (Rachelson,2017). Items like plastic bags would seem like a plausible recycled products but in actuality, they can clog the machines and can potentially cause technical issues (Rachelson, 2017). Another obstacle as mentioned is the ability of the recycling facilities to be able to sort and process materials which are due to not having the proper funding (Gelles, 2015). The recycling companies that do accept all of the materials collected by the city have their price for different commodities (Gelles, 2015). Since the main purpose of these recycling companies is to make a profit if a product is too costly or it is rarely in demand it will likely end up in landfills (Gelles, 2015).

Also, the US shipped over 1 metric ton of waste abroad to other countries, further overwhelming them, due to the relaxed environmental rules and cheap labor (Cho, 2020). In the US there is no federal recycling program and there is insufficient investment in facilities (Cho, 2020). Since plastic presents one of the biggest challenges, companies rarely buy recycled plastic and virgin plastic is cheaper due to the process (Cho, 2020). Some of the solutions to this are developing the domestic market, having better recycling practices (eg. placing it into the right bin), education, and policy implementation (Cho, 2020). Until there is a proper recycling system there is still a problem in the system as many still end up in landfills.

Materials and Recycle: Packaging

Packaging is one the biggest contributors to the total waste since it is meant to be thrown away once it is done serving its purpose. So one of the focuses of creating a sustainable product is to not ignore the impacts of the packaging. One of the best ways to lower packing waste is to create it with material that can be biodegradable or recyclable. Some example includes plant-based packaging (eg. cornstarch packaging), dissolvable foam (eg. green cell foam), and compostable packing (Nicasio, 2021).

Other ways are designing a greener packaging is using just one material, using commonly recycle products (eg. PET plastic), and having a how2recycle clear label (Shova, 2016). Since it comes to the end of use the user is responsible for the packaging it must also serve as a way to communicate with the user to properly throw it away. How2recycle is a label that makes it clearer for the user to properly sort the package, the label includes material type, components type, and special instruction (How2Recycle, n.d.). Some examples of brands that design with environmentally conscious packaging design are the apparel brand Allbirds and Patagonia. Allbirds use the same box for shipping and retail and the box is made of 90% recycled material (Pregis, 2020). Patagonia uses mostly recycled material in packages and they give instructions on their website on how to recycle their garment (Pregis, 2020). Packaging is something that should not be overlooked when designing since it is a part of the product and has a huge environmental impact.

Design and Redesign

Design is the most crucial step; it is where all decisions can be made and whether the product is environmentally friendly depends on the design stage. It is where 80% of sustainable choices are applicable because they will affect most of the stages of the life cycle of the product, and this is where the concepts displayed in the model can be viable (Inside Battelle, 2021). This is where we determine the materials, device design, manufacturing process, packaging, distribution, and disposal (Inside Battelle, 2021). Life-cycle analysis can be used for specific design cases, such as design for the environment or design for rebirth, where there are applications of quality management, reducing the components, or simplifying materials that can be possible for future design, manufacture, and disposal (Mann, 2018). Another approach is to design for disassembly, where it aims to have the product be modularity so that the product can be more effective for recycling. These are concepts of what it means to design environmentally consciously with the consideration for recovery.

To redesign is to consider all the dimensions/elements of sustainability/sustainable design and analyze the sustainability performance in terms of each of the above elements, and assess how it might be improved. For this model, redesign considers all of the elements of sustainable design but there are cases where they only focus on one point of sustainable design such as the efficiency of the material. An example of redesigning by using one element of design can be seen in a case study that closely looks at a dialyzer and redesigns it to reduce its material. They redesigned a dialyzer by disassembling it into five main components and analyzing the materials. They determined that polycarbonate has the most significant mass and worse environmental impact. So they sought out a solution to limit it to a smaller weight (17%) while keeping the same function (Hanson, 2009). They could find a solution through proper design planning with life analysis. This is a clear example of downsizing a material and keeping its functionality. Another example of the case that only focuses on redesigning for efficient use of the material is Poland Spring. This can be seen by their bottle cap. In 2005 the cap was thicker and required

14.6 grams of resin and in 2012 it was much slimmer and only required 9.2 grams of resin (Stevenson, 2012).

Objective 2: Apply the framework for sustainable design to frannie

Case study: Frannie, the assistive device for crocheting

Crocheting is an activity that can relieve stress and allow the participant to be creative, yet older people who enjoy the craft can be limited by their arthritis. Crocheting requires long durations of repetitive hand motions. Over time, the joints get sore and swell so that the pain can be unbearable for those with arthritis. However, no device is currently on the market that can aid mobility for those who want to crochet.

So my team and I designed a crocheting device to reduce wrist motion for those with arthritis. We want to have a device that can rotate a crochet hook without wrist rotation. Therefore our design has a disk mechanism and pulling lever to rotate the disk by just our thumb. Since the user is only turning a lever to trigger the rotation, it limits the wrist motion making it more comfortable to crochet. This type of mechanism has not been seen on any of the crochet devices out there, and it could be used as a solution to give comfort to arthritis users.
In terms of the environmental impact our product weighs around 4.2 ounces, and if we multiply that by 100 Frannie, it is 420 ounces of waste. That might not seem a lot but add that with the rest of the assistive devices out there; that is a lot of waste contributing to the already substantial amount. There are over 2 billion tons of municipal solid waste (“*What a waste 2.0”*, n.d) globally every year, and eventually, it will reach 3.4 billion tons by 2050 (“*What a waste 2.0”*, n.d). Therefore we must design products like Frannie to become more sustainable so that it does not contribute to waste. To do that, the model can be used as a guide to achieving the minimization of waste.

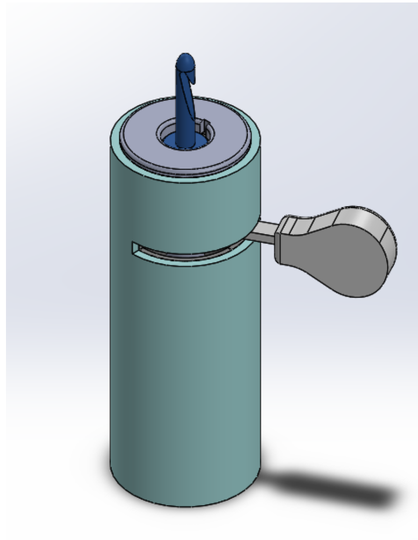

Figure 5*: Frannie's design*

The application will consider 4 relevant elements of this integrative framework in the design of ‘Frannie’: recyclability, design, durability, and repairability. Frannie, described in the introduction, is an assistive device developed in the Mechanical Engineering-focused part of this project. The 4 relevant elements are introduced as objectives 2a through 2d:

Objective 2a: Different aspects of materials and recyclability potential

Many materials can be sustainable, but they have to meet criteria so that it does not limit the device's function. When designing, it is important to consider whether the product can be recycled and can be done by giving users options and different ways to recycle their products. So, researching the material that can be applied in the Frannie and waste management considerations will be the goal of this objective.

Objective 2b: Design with a focus on the reduction of material

A device can have an excessive amount of material; therefore, designing for effective use of material can limit waste and raw material uses. So simplifying the type of material in the device can make it easier to reduce its size—this objective looks at reducing material quantity in our machine and provides recommendations on ways to achieve it.

Objective 2c: Durability

A product must be durable to withstand time and usage. Being durable can prolong the product's life, and it can limit the cost without constantly replacing it. So there will be tests conducted to test the durability of Frannie. I will also seek out recommendations and other alternatives to have Frannie be durable.

Objective 2d: Repairability

Repairability can prolong the life of the device, extending its use and avoiding or delaying disposal. The device should have a sturdy quality, so it does not break easily, and if it does, it can be easily repaired. That can be done by having removable parts or making the device from one common material. Therefore, in this objective, I will look at ways to make the device easily repairable and methods for users to access options to repair their products.

The four objectives will be the project's primary focus of application: finding ways to make the Frannie crochet device as sustainable as possible and maintain its functions.

Objective 2a: Different aspects of materials and recyclability potential

When it comes to choosing which materials to consider, the materials must be suitable for Frannie, which means they must fulfill the functional requirements. The requirements asked for the product to weigh less than 2 lbs overall, and it has to be a smooth material for it to rotate with little friction. Based on that, the materials should have similar properties to plastic because they need to be lightweight and have the potential for recycling. Therefore, the materials that will be analyzed are aluminum, arboform (liquid wood), PLA polymer (a bioplastic), and bamboo. The research will identify the benefit of the materials in terms of recyclability, manufacturing, and their flaws and potential issues.

Aluminum

With a density of 2.6898 (g/cm^3), which is ⅓ of the weight compared to steel and copper, it is considered to be one of the lightest metal materials (azom, 2005). It is durable, moldable, and corrosion-resistant, suitable for sanitization (azom, 2005). Aluminum fits the requirement needed for Frannie; it is a product that is easiest to recycle. Around 75% of the original aluminum is still in use, and compared to virgin manufactured aluminum, recycled aluminum only takes about 5% of energy to produce. To recycle aluminum is a mechanical process where the products are shredded and are melted down to be placed in a mold to make ingots or sheets (Leahy, 2019). Although it might seem an ideal material, one factor why aluminum might not be the best choice is its price. It is three times more expensive than steel for raw aluminum, and in assembly, it is twice as expensive (Chapman, 2014). This is due to the high demand and the frequency of aluminum use since it is also used in soda cans or automotive. It is one of the most flexible in terms of application, but the flaw is in its price.

Liquid wood

Made from a mixture of cellulose, hemp, fax, and lignin, arboform, nicknamed: liquid wood, is a completely biodegradable material (Dumitru, 2013). Abroform looks and feels like wood, is moldable, and has the properties of plastic; it combines two of the most commonly used materials (“Liquid wood”, n.d). It can be processed like thermoplastic through injection molding, which can be used for many applications (Dumitru, 2013). It can be used for furniture, toys, food containers, and almost anything that uses plastic. It is also durable as the modulus of elasticity is higher than the common plastics like polyethylene, with high stiffness (Nägele, 2002). In terms of the environmental impacts and reduction of CO_2, abrofrom stands out from other materials. Since it is made from renewable material, it can be incinerated without emitting more CO_2, and it degrades similarly to wood (Nägele, 2002). The disadvantage is that abroform is heavier than regular plastic, and it is almost two times the cost to manufacture compared to polyethylene (Dumitru, 2013).

PLA polymer

PLA is a bioplastic that is recyclable, compostable, and biodegradable, and it is a common commercially available plastic (Krieger, 2018). It is made from plant-based materials such as corn sugar, unlike regular plastic, which uses fossil fuel (Krieger, 2018). For 3D printing, this is the most commonly used filament, and this is what Frannie is made of. The polymer is complicated sustainable-wise; there are a lot of trade-offs and aspects that are overlooked. To start, it will take 2.65 kg of corn to make 1kg of PLA, and if it replaces standard plastic, it will take away 715.5 million tons of the global food supply (V, 2019). However, it is biodegradable only in industrial composting conditions, and if it is in nature, it will take 80 years (V, 2019). It is recycled only without the contamination of other plastics (V, 2019).The current way to recycle PLA is to have been in "mix recycling" due to poor infrastructures (Rezvani, 2021). This can contaminate the plastic, and the quality of recycled PLA is not the best (Rezvani 2021). .Still, it is a better alternative to other plastic polymers, and in 3D printing, this is one of the bioplastics that works best (V, 2019).

Bamboo

Bamboo is one of the fastest-growing grass that is durable and flexible in application, and it is one of the most sustainable products in the world. It has a higher compressive strength than concrete and higher flexural strength than wood (Spacey, 2018). Since Bamboo is a natural material and is grown mostly in Asia, if they are manufactured in the US, it will require travel which means there will be transportation emissions (Carter, n.d). Bamboo can be recycled, but if it does not mix with chemicals, such as preservatives that are meant to preserve the shape and prevent rotting, it cannot be recycled if it is not organic (Kukreja, n.d). Although it is able to be biodegradable, it will take longer if it has chemicals (Kukreja, n.d). Another factor of bamboo is that it is vulnerable to rot and can have a lower life span which might not be a problem in the case of Frannie but in other cases (Spacey, 2018). Also, the many invasive species in many parts of the world can cause a lot of issues with bamboo products.

The materials listed have the potential to be the materials that are suited for Frannie. A product should be made from one material for recycling since a combination of materials will make recycling more complicated. All of the materials listed can be either recycled or biodegradable and have the potential to be in a closed loop. It is noted that all materials have flaws, such as price, so there is a trade-off when any of the materials is chosen. There are also still flaws in the recycling system; most of the materials have risks of contamination. That is why we also need to consider if the products can be biodegradable as well if they cannot be recycled properly. The aspects of each material are listed in table 1.

Material	Readily available	Complete recycling	Negative	Positive properties	Durability
Aluminum	Very common	recycled repeatedly without losing any quality	20-30% more expensive than steel	Lightweight	90 MPa-690 MP
Liquid wood	Made from fibers excess from paper manufacturing	biodegradable and combustible like wood	Relatively newly invented materials. It can be more expensive than some plastic	made from 100% renewable raw materials. Similar to plastic, it's durable	modulus of elasticity is higher than the common plastics like polyethylene, with high stiffness
PLA polymer	Common/ 3D printing materials	biodegradable in industrial composting conditions	80 years for PLA to decompose, only biodegradable under industry	Durable, cheap, the life span of 10 – 20 years	7,250 psi
Bamboo	Common in Asia (80%) if manufactured in the US it will need to travel.	Recyclable if they're free of chemicals. Biodegradation can range from weeks to years	Rot, lower life span	Can be used for biofuel, strong, lightweight, building material	It has a higher compressive strength than concrete and higher flexural strength than wood

Table 1*: 4 materials properties*

Objective 2b: Design with a focus on reduction of material

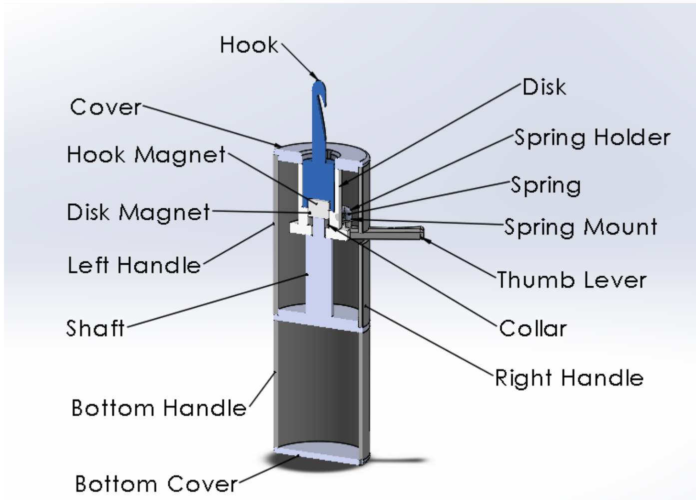

Figure 6*: The internal components of Frannie*

Reducing material size is the best way to limit the number of waste and energy. At first glance, it might seem like our device is too small to contribute a significant amount of waste; however, considering that each unit weighs around 4.2 ounces, 100 units would produce 420 ounces of waste. It also requires a lot of energy since the energy to produce 1 kg of PLA granules ranges from around 14 to 17 kWh/kg (Cerdas, 2017). To compare, a standard kitchen oven requires around 2.3 kWh per hour (ElectricityPlans, n.d), so if 1 kg of PLA is produced the oven needs to be on for more than 6 hours. To 3D print, a 5cm tall print will take 20 minutes and around 120 KJ (Kilo Joules) worth of energy which is equivalent to a 100W light bulb switched on for 20 minutes (3D Print Works, n.d). There are two ways that Frannie can be reduced; one is the handgrip, and the other is the overall size of the collar.

Our hand grip currently has the most unnecessary mass as it weighs around 2.4 oz on its own and has a thickness of .2 inches. It is too bulky, which also does not comply well with the weight requirements (that will enable easy handling by users) since it should be lightweight.
Since the mechanism is only 2.28 inches and the bottom portion of the device is empty. It can be made around 1/10 inch less, which will take away .4 inch. Secondly, if the magnet can be replaced with a smaller one, we can reduce the diameter of the base by .1 inch and still give enough space for the disk. So if Frannie currently has 0.05 kg of PLA, and we reduce it by around 1/7 just by making it skinnier; It will require only around 0.043 kg of PLA, which means we also use less energy. If 100 Frannie is produced and if it will take 1000 hours to produce it and now that there is less material the time can at least be reduced by 1/10 it will only require 900 hours.

Objective 2c: Durability

To have a product live a long life cycle and withstand time and external and internal damages, it must be durable. To determine whether Frannie can withstand potential damages, to obtain that data some tests were done on the Frannie prototype. Then based on Frannie's degree of durability I will discuss other improvements that can be made.

The three components that are likely to fail are the hook, spring, and lever since they are the ones with the most stress on them. So they were analyzed to determine what is the maximum stress and force that they can endure, this was done by having weight pulling down the hook and lever until it breaks. The spring and lever were tested by pushing it many times by hand and changes to the mechanism were recorded. The figure below showed the test that was done on the hook:

***Figure** 7: Test done on hook*

The complete results are listed below:

Analysis

Lever	Maximum bending stress = 10.73 Mpa
Hook	Maximum stress = 52 N
Spring	Spring constant require = .733 N/cm
Crochet force	5 N

***Table 2**: Analysis of the Frannie's prototype*

Test

Hook	Failed = 50 N
Drop	Withstand 3 ft
Cyclic test	Lever pushed 500 times without mechanism fail

Table 3*: Tests of the Frannie prototype*

The device is made from PLA, a tensile strength of 7,250 psi, is already a durable material but based on the analysis it can withstand damage overall (Airwolf 3D, 2017). The maximum for the Lever and hook require a considerable amount of force for it to fail or be damaged.
Since we only need 5 N to crochet, the lever will not likely bend. Also, it can be dropped around 3 ft without breaking, and the hook also needs a 50 N of force to break. PLA also has a life span of 10 – 20 years indoors, so both exterior and interior of Frannie (which is both made from PLA) will last a long time (Van den Oever, 2017).

Objective 2d: Repairability

The best way to have a device repairable is to have it be modularity so that it can easily be removed and parts can be replaced. A simple design, furthermore, can allow the repairer or the users to fix it without complicated tools or skills. Frannie has a simple, mechanical design; and the parts can be removed. There are 14 pieces of components, and the hook and paddle are removable. The collar is printed in halves, and they are put together by glue. Which is difficult to remove; however, it can be designed to be opened up easier. Figure 8 below shows that it can be designed to have a latch or a snap lock to open and close more effectively. Another consideration is to have spare parts, hook, and paddle, that come with the products.

Also, communication with the users through packaging is a way to provide more instruction to repair. One example is videos on providers' websites can be put online giving users the option for self-repair. We can also provide free repair by giving instructions on the package to have it be sent back for repair.

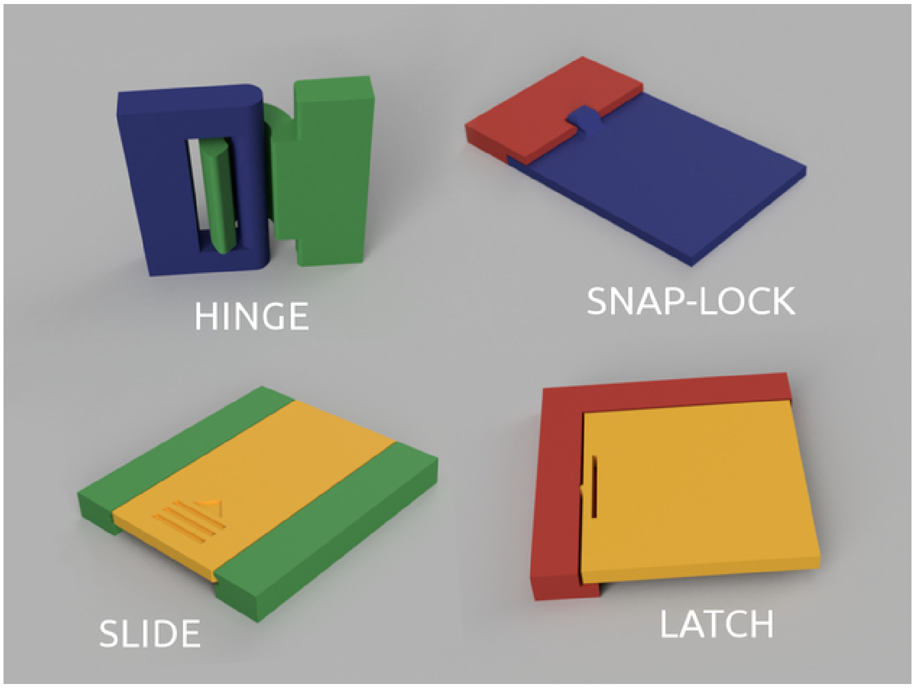

Figure 8: *Print from BlacklightShaman on Thingiverse*

Discussion

From the results, it can be determined that there are options or considerations coming from the concepts in the framework that can be applied to Frannie. There are, however, trade-offs due to the incomplete status of testing; the application does not aim to be perfect but aims to be an example and reference. The following objectives investigate the four different types of options relevant to this case. These options do not try to interrupt the functionality or the overall design but instead, work around it. So I will further discuss the results from the four objectives in detail, along with their limitations.

Objective 2a: Different aspects of materials and recyclability potential
Four materials were chosen and analyzed since they are best suited for the functional requirements for Frannie. These materials have similar properties, which are lightweight, durable, and have the potential to be recycled or have a minor negative environmental impact. Starting with aluminum which is the most recyclable material on the list since it is non-corrosive and one of the most common materials that can be recycled in the city recycling system. However, if manufactured and if Frannie were to be marketed, the price might be too expensive compared to the rest of the materials.

Second, liquid wood is the best when it comes to being biodegradable and has the most similar properties to plastic. However, it is a newer material, so there is a lack of information when it comes to recycling, and its possibilities are unclear.

Third, PLA polymer was used as the prototype material and the only material actually explored. It is a common material, and it is both recyclable and biodegradable. There are however a large amount of energy intake in the extraction stage and recycling is flawed.

Lastly, bamboo is a highly biodegradable material, but it is not a material that can be recycled in the city system.

There are extreme flaws in the current recycling system, and half of the materials listed cannot be collected as recycling materials. So until there is a change in the system, we must consider that the product can be biodegradable. That is why three of the materials can be biodegradable so that if there is a chance that they cannot be recycled, they will not be a part of the collective landfill wastes. It is noted one of the limitations of this application is that Frannie was only made with PLA, and the other materials were not explored. Therefore, it is unknown whether the materials listed can be suitable for Frannie or if they could be better than PLA. Also, for us to know whether it is completely recyclable or biodegradable, it must be tested. That is something that can be explored in future designs. Despite the limitations, these are still plausible materials that can be applied or explored. We also must understand that despite being labeled as sustainable materials, there are flaws and other aspects like energy input that should be considered.

Objective 2b: Design with a focus on the reduction of material
As discussed in the result, there are a couple of ways that Frannie's energy usage and production of waste can be reduced, while still not detracting from the fundamental goals and function of the device. For Frannie, there is excess internal space that can be reduced, and parts like the magnet can be switched out for a smaller size. Any product that can reduce its size, even if it is just one part, can significantly make a more positive, sustainable impact.

Objective 2c: Durability
Since this is an assistive aid for arthritis users, there is a low chance that the users will input a large amount of force. Frannie requires 5 N of force to trigger the device; it will be less likely that the user will ever go past that standard force. In the case that it is dropped or some other damage is inflicted, the device will still maintain its functions and usability. It is better to prevent than to cure, and having a durable device will increase the usage and keep away from landfills.

Objective 2d: Repairability
In the case that it does break, having an option to repair it is essential for a sustainable design. The options are listed in the results, and there are probably more ways that it can enable repairs. Also, designing with different options to repair will positively influence the chance of prolonging usage and quality of the product, which are aspects of circular economy. One trade-off is that if a part (eg. the hinge) is added, that means there are more materials, but if other components are

reduced, the additions will not be substantial. Also, Frannie is designed with two replaceable parts - the hook and the lever paddle - which are two of the most vulnerable to damage due to the force input. Therefore, the two parts can be replaced and if replacement parts are included it will make it easier for the users to fix the device.

The results do not pose a solution; instead, it is a guide toward a sustainable design. For a framework to be applied to a larger project, it must start small. Although Frannie is a simple design, the concepts in the framework can be successfully applied. It proved that a sustainable framework could be utilized even with something small in size and a simplistic design. It is noted that we used four objectives from the framework, which, if incorporated together, might overlap with each other, such as building for repair and reducing materials usage. Other points of discussion are the limitations of the testing of Frannie. As mentioned, this is a case that only applies to PLA as other materials have not been tested. So durability or the compatibility of the other material is still unknown.

The recycling process for material like liquid wood is unknown since it has not gone through the standard city recycling process, and since it is still new the vulnerability to contamination is unknown. Also, PLA is flawed as it can be only biodegradable in industrial composting plants, and it will take decades to degrade in nature. As mentioned, there are flaws in the recycling system, and Frannie should be tested with all four materials to ensure that it can either go through a basic recycling system or biodegrade in a short amount of time.
Another factor is making Frannie as small as possible due to the limitations of resources, like advanced machines for printing, and time.
The last note is that the sustainability features should not interrupt the functionality for future reference; the features that were mentioned must be tested to ensure that Frannie is still able to maintain functionality. Therefore, more research is needed to test out all of the possibilities.

While utilizing this framework, not all the concepts can be applied, but even applying one can still provide a possible impact. The framework aims to provide what considerations can be made when designing a product to make it more sustainable.

Conclusion

The model of sustainability design was produced to be a tool for designers to visualize the considerations that can be made to produce greener products. Using the model that was created it was able to apply to a case of an assistive device that is in the design stage. Using Frannie as a subject of an application, despite its simplicity in the design there were considerable amounts of recommendations and research that was able to be implemented. The model not only serves as a tool for one type of product, an assistive device, but it can apply to any type of product design. As the design is the most crucial step, designers must acknowledge the possible negative impacts of their products. The model showcases the possibilities in sustainable design thinking and from that comes possible resolutions to the waste problem.

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