Developing a Ranking System for a Product's Fitness in the Circular Economy - A Case Study in Modular Ski Poles

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Abstract

As the importance of designing sustainable products grows, the importance of developing in tandem with the Circular Economy also grows. This paper presents and demonstrates a multi criteria decision making method of ranking products in their fitness for the circular economy. This methodology uses an analytical hierarchy process and pairwise comparison matrices to evaluate the criteria and scores assigned to each. In doing so, this process compels the designer to evaluate their systems based on four major factors: repairability, reusability, recyclability, and sustainability. The method was applied to a case study of ski poles comparing a new design for the circular economy with three existing ski pole systems. It proved that if a system is designed with these factors from the beginning, it will better fit into the circular economy. The CE realizes benefits for the consumers, the company, and the environment.

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“The truth is not complicated. Skiing succeeds whenever and wherever it sustains the primal experience that has forever attracted its lovers: rising up a mountain into the sky, gliding through a spruce forest hushed by snow, thrilling at the fast descent, floating through an ocean of weightless powder, and looking back at the tracings etched on the snow... stored remembrances of a passage through space and time.”

-John Fry, The Story of Modern Skiing

1 Introduction

1.1 BACKGROUND

What happens to all the broken ski poles?

Last year, while skiing with my dad, he was hit by another skier. His ski pole took the impact and it broke in two. We went to the bottom of the mountain and he picked up the new set. When the ski tech asked what he was looking for, he replied “whatever is the cheapest”. He got the new poles and we drove home. We unloaded our skis and gear, and he tossed the old poles into the garbage bin. The poles, one broken, one still in good shape, upside down and hanging out of the bin struck something in me. One of those poles was in perfectly good shape. How many times a year do these unbroken poles get tossed?

A few days later, my sister’s fiancé broke his poles. It hit me that so many skiers break ski poles. When this happens, the break will typically only occur on a single pole. So what is everyone doing with the unbroken pole? And how are they treating the waste management of their other pole?

I decided to set out to explore this problem. What is happening with all ski poles? Are people attempting to repair them? Throw them out? Recycle them? And specifically, what is happening with the *unbroken* ski pole? Are they being thrown out as well?

The circular economy is something that has been gaining momentum in the past several years. The idea of keeping a product in use for as long as possible not only is better for the environment, but has value for the user’s as well. This problem that I noticed with ski poles goes against all the tenants of a circular economy. The poles cannot be repaired, and reuse really only becomes possible when the user specifically keeps the unbroken pole to use for mismatching.

Sustainable ski poles exist - ski poles made with better materials and manufacturing processes. But, being a “green” product doesn’t only include the sustainability of the product. Arguably, it is *more* important that a product’s entire life cycle is considered and trying to achieve sustainability through every aspect.

Ski poles are made up of four major components: the shaft, grip, basket, and strap. A diagram of a standard alpine ski pole is shown in Figure 1. In the way that nearly all ski poles are manufactured now, the grip is epoxied onto the shaft. The strap is occasionally removable through an exposed screw, but not made to be repaired. The basket is the only

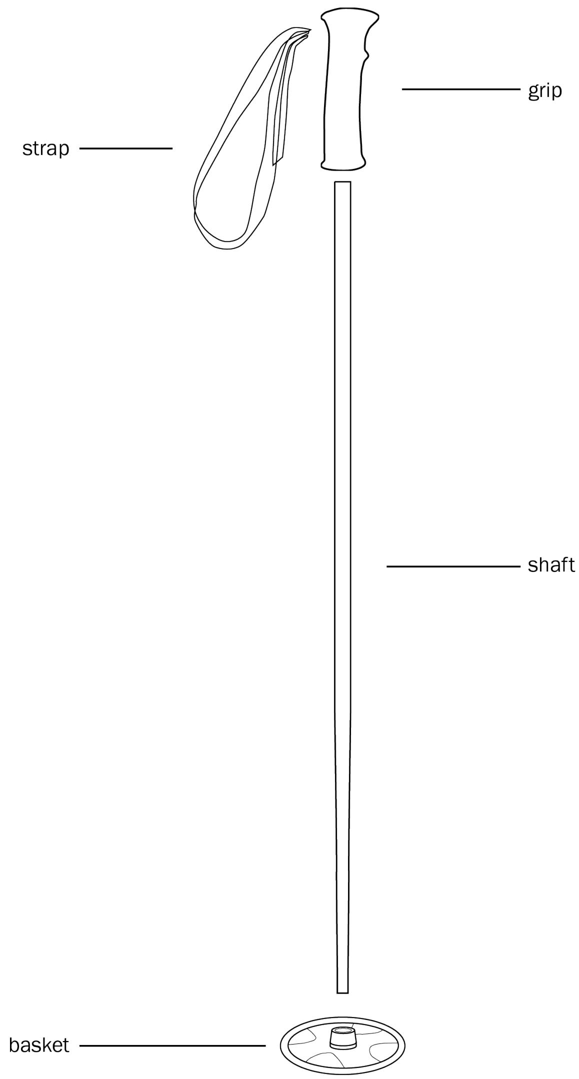

Figure 1. Main Ski Pole Components

part of the pole that is often made to be replaced. Different poles have different methods of connecting the basket to the shaft, but most include a basket attachment part epoxied onto the shaft. If the shaft were to be damaged, repair would be nearly impossible on any of the existing systems due to all of the existing parts.

1.2 USER SURVEY 1

Before diving into this problem and solving it, I needed to understand what the problem really was. How are alpine recreational skiers treating their relationship with their ski poles? How are they dealing with them when they break? I conducted a primary user questionnaire to try and answer some of these questions.

The questionnaire was sent out to contacts that are skiers (beginners to experts) and posted on Reddit. This survey received 84 submissions. A copy of the questionnaire is show in Appendix A.

One section of this questionnaire asked respondents to say how important each factor was when buying ski poles (1 being not important at all, 5 being extremely important). The factors were cost, weight, durability, sustainability, and appearance. The goal of this question was to see what the consumer cared about the most when purchasing. The averages of the responses are shown in Table 1.

Table 1. Averages of Importance when Purchasing Ski Poles	
cost	3.8
weight	3.4
durability	3.8
sustainability	2.8
appearance	3.0

Sustainable ski poles are on the market for a high price. But, is that really what users care about? Does a product marketed as sustainable mean the customer will pay a higher price? From these responses, we can see that sustainability is the least important consideration when purchasing ski poles, and cost and durability are the most important. 80% of respondents want to pay $100 or less for a pair of ski poles. The fact that these are what people care about the most highlight the fact that ski poles are a good candidate for a product designed for the circular economy. The circular economy provides products that are reliable, repairable, and should therefore save the consumer money over the product's life.

This survey also asked if the respondents had ever broken or damaged their ski poles. 62% of people had responded that they had. If this is filtered to look at only the people who considered themselves advanced or expert skiers, that number jumps to 77%. This increase can likely be attributed to the fact that advanced and expert skiers ski more aggressively and much higher speeds. Breaking ski poles is not an uncommon event, and the likelihood increases as the skier ability does. 61% of respondents reported that the break or damage occurred in the shaft of the ski pole.

The problem with this, though, is that ski poles are not repairable. More specifically, if the damage were to occur in the shaft, repair would require removing the grip and basket attachment, having a spare part to replace it with, and reattaching the components. Ski poles are not currently designed to handle this type of repair. Thus, there is virtually no way to fix a ski pole once it breaks. Further, that renders the pole that didn't break as unusable. Ski poles are not sold singularly, so the entire set is rendered unusable once one breaks.

The next question asked what the users did with the poles once one was broken. 51% threw both the broken and unbroken pole in the garbage. Only 8% of respondents had attempted to recycle them. 14%, however, kept the unbroken pole to mate with another unbroken pole. That shows that there are some who recognize the value still left in that pole, yet there is no system in place to realize this value, and instead resort to having a mismatching set.

This initial user survey provided a lot of valuable insight into how skiers interact with their poles throughout their lifetime. They look for a low cost, durable alternative. The majority of skiers have broken or damaged their poles, and it is mainly the shaft that breaks. The set is then thrown away or recycled. There is, however, a minority of skiers, who keep the unbroken pole to ski on as a mismatched set. This information led me to the conclusion that ski poles are a viable candidate for the circular economy. This would include designing a system that is easy to repair and has a plan for end of life management, something that current ski pole systems are lacking in.

1.3 SIGNIFICANCE OF STUDY

The goal of this study is to create a methodology to rank products or concepts on their fitness to the circular economy. Through a multi-criteria decision making analytical hierarchy process and a system of scoring the products in repairability, reusability, recyclability, and sustainability, a number of products can be compared and ranked and used to make optimal design decisions and choose the between alternatives. This methodology can be used to compare different competing products, or it can assist a designer in comparing multiple concepts. This method can assist the designer in showing where a specific concept is not meeting the specified requirements for the CE.

Having a world in which skiing is possible relies heavily upon the way we take care of our planet. It is a simple fact that if temperatures rise, a sport based entirely on snow conditions cannot be sustained, yet very few winter sports products are designed for the circular economy. It is hypocritical, then, that most of the products designed for this sport are in fact, taking the sport away. These products (and companies that make them) will only survive as long as there is an environment in which to use them. If the sport of skiing is in jeopardy, then businesses that capitalize from the commercialization of the sport must be proactive in helping to ensure its longevity. This thesis, utilizing a case study of ski poles, attempts to right some of the wrongs produced by this industry.

2 Literature Review

HISTORY OF SKIING AND SKI POLES

Skiing has existed for over 6,000 years (Fry, 2006). It is one of the earliest forms of winter cross country travel and was used as a means for hunting and waging war. Skiing became a recreational sport in the early 1900s as ski areas began popping around snowy regions around the United States and Europe. The decades following WWII, however, revolutionized the way we ski. Technological advancements allowed for lifts and gondolas to bring people higher up the mountain, snow making and grooming capabilities, and new materials and manufacturing methods to create better gear and equipment.

The first skis with a polyethylene base meant skis could be lighter and faster. In the early 1970s, the popularity of shorter skis grew. These shorter skis meant that it had a tighter turning radius, and consequently, created close snow bumps on the hill, known as moguls. These shorter skis literally changed the face of the mountain and disrupted the industry of skiing (traditionalist skiers who hated this new landscape had “short skis suck” bumper stickers on their cars). A hard shelled, buckled ski boot was another huge advancement to the sport. It meant that the skier could put pressure on the side of the boot in order to get their ski on the edge and allow the knee to flex forward, resulting in better turns at higher speeds.

Ski poles, on the contrary, have not had any recent industry disrupting changes. The purpose of a ski pole, most basically, is to aid the skier in initiating their turn. As the lower half of the body is controlled by the skis and leg movements, the upper body’s movement is aided by the movement of the poles. By flicking out of the ski pole, the skier can focus the upper body’s movement in the direction of the turn. In modern skiing, a well-groomed run rarely requires the use of a pole. In skiing off-piste (off the groomed run), however, the pole is beneficial if the skier completely releases the edges from the snow or if there is mid-turn jumping (Lind, 2013). Ski poles are also used as a means of forward propulsion and restoring balance.

A major innovation came about in 1959 when Ed Scott created the first taper aluminum ski poles. Prior to that, they were bamboo or steel and Scott claimed “poles were designed stupidly or unimaginatively at the time”. The poles were “whippy and almost impossible to flick in a quick, accurate plant” (Fry, 2006). He instead, decided to use a thin-walled aluminum to tube and add a light basket. Carbon fiber became a popular choice as well, but they are more expensive and, unlike aluminum which can be bent back into shape if deformed, they tend to completely snap. Many have their preferences for what they like, but even today, over 60 years later, the tapered aluminum shaft is by far the most popular choice.

Ski equipment has changed drastically over the past century and will certainly continue to do so. New skiing techniques drive new designs just as new designs drive new skiing techniques. The history of skiing is long and the sport has maintained its popularity, especially over past two decades. According to Verified Market Research, the ski market was valued at 1.23 billion USD in 2018 and is projected to reach 1.61 billion USD by 2026. It's a sport that has captivated millions of people and offers something for every level of skier.

MODULARITY

As today's society has embraced rapid change and new buys, products are being purchased and thrown out at an increasing rate. Modular product design may be the key to this problem. A module, as defined in *Controlling Design Variants: Modular Product Platforms*, is "a building block with defined interfaces" (Ericsson, 1999). Having these different building blocks opens up new possibilities that may begin to solve some of the complex issues of our take-make-waste linear model and facilitating the creation of a more sustainable product. According to the authors of *A Modular Design Approach to Support Sustainable Design*, "the modular design approach allows designers to focus on increasing the sustainability of a product in terms of recyclability, disassembly and reduction of resource usage at the conceptual stage".

The benefits of modularity are vast. The positive effects of designing modularly at the product range level include: product changes due to new technologies only impacting a limited number of modules, reduction in product development lead times as parallel development is possible, improved quality as each module may be tested prior to final assembly, easier servicing and upgrading, easier administration on quoting and planning, and efficient customization of specific modules (Ericsson, 1999). Further, there are benefits that the company may directly benefit from. As new generations of a product are released, carryover modules (modules that haven't changed between iterations) may be used from one generation to the next. The company may have planned product changes, parts of the product which they intend to develop over time, meaning they can better satisfy customer needs and only impacting one module. The brand identity of the company may also be easily updated as trends and fashions dictate change. As service and maintenance is often a customer requirement, service modules may allow for quick repairs or replacements to the damaged module. Designing with modules will allow the customer the possibility to upgrade their product in the future. Lastly, modularity facilitates the ease of recycling so long as each module is made up of as few materials as possible.

It is clear, now, that designing for modularity has a huge number of benefits, both to the consumer and to the company. Ericsson and Erixon propose a method, Modular Function Deployment, to find the optional modular product design outlined in the following five steps:

Step 1: Define Customer Requirements

This step is necessary for all product design and ensures that the correct customer requirements and needs are being met. This demands a thorough understanding of the market, who the customers are, and what is important to them. It is also critical to understand the relationship between the customer requirements and the product properties, ensuring that the proposed idea is creating a benefit to the target customer.

Step 2: Select Technical solutions

Once the customer and their needs have been fully defined, it is possible to proceed with a more technical view. The product must be broken down into their functions and corresponding technical solutions, known as a functional decomposition. If each component achieves functional independence, an efficient modular product design may be achieved and interaction between the modules is limited.

Step 3: Generate Concepts

In this step, module candidates are picked out. The ideal number of modules must be determined by analyzing the time required for assembling the finished modules. At this stage, different module concepts can be developed and ideated upon to determine the best solutions.

Step 4: Evaluate Concepts

As a concept is generated, so are accompanying questions regarding manufacturing, production, and product development, and most importantly, how much better the modular concept is compared to the existing design. The interface between two components and the flexibility that they offer must be evaluated.

Step 5: Optimize Module

The last step is to write out all the technical information, cost targets, and planned future development of the finalized modules. Each module may be focused on separately and improved on its own.

In following these steps, an optimal modular product may be designed. It will only be a successful product, however, if the company's strategy and goals are explicitly stated, understood, and reflected in the product. These company objectives must clearly be visible in the product and supported by the modular design. Further, the company must always be a step ahead of the competition and be prepared for the next iteration of specific modules to continue providing the most value to the customer.

In a Bryant et al. developed a redesign method to support sustainable design of products. They looked to modularity to assist them with this goal. They found that by beginning in the conceptual design stage, "the scope of redesign and the potential product improvement increases (Bryant, 2004). They found that in redesigning 12 different products to enhance their modularity and part count reduction, a more sustainable product was generated. They attributed this to ease in disassembly, recycling, dismantleability, serviceability, assembly, and human factors. They chose six aspects as prioritized life cycle factors and used pairwise comparison matrices to weight them.

CIRCULAR ECONOMY

In short, the circular economy aims to eradicate waste. By designing products disassembly and reuse, their "life cycle" may turn into "life cycles". In moving away from a take-make-waste linear model, a circular economy may replace disposal with regeneration (Nguyen et al., 2014). This whole model centers around the idea that materials have value and may be used again and again, rather than frequent disposal. In looking at consumer-goods industry "about 80 percent of the $3.2 trillion worth of materials it uses each year is not recovered" (Nguyen et al., 2014). The authors here also discuss the role that the company must play. They state that rather than selling, renting would ensure the company receives all materials back. For products that are sold, companies should have incentives to guarantee their return and then create reuse opportunities. It is clear, then, that in the circular economy, the company must consider this end of life management from the beginning. When a product finally reaches the end of its useful life (cannot be remanufactured, reused, or refurbished), recycling becomes the next important step in the materials life.

In 2013, McKinsey set out to map the benefits of the circular economy and define how companies may increase their financial performance. This powerful assessment shows how there is benefit for all parties involved in turning towards a circular economy. They defined six circular economy activities that have the potential to benefit companies and industries: regenerate (renewable energy and materials, share (prolonging lifespans), optimize (improving product efficiency), loop (keeping materials in closed loops), virtualize (delivering goods and services virtually), and exchange (replacing out old materials or technologies) (McKinsey, 2017). They reviewed 28 industries and found that all of them could benefit by adopting at least 3 to 4 of the above activities while 10 could benefit by adopting 5 to 6.

There has been a growing consensus among activists, world leaders, and politicians alike that better indicators for a company's circular economy performance are needed. In June of 2020, the European Union presented the new Circular Economy Action Plan (CEAP), The European Green Deal. This action plan has the goal of making sustainable, circular economy driven products the norm in the European Union. It has become a major piece of legislation to make this transition from the linear economy to that of one more circular and sustainable. It has the goal of achieving climate neutrality in the EU by the year 2050. This European Green Deal advances on the CEAP that was presented in 2015. The action plan mapped out 54 points that targeted landfill, reuse, and recycling. The collaborative approach between policy makers and stakeholders mean that they were able to rethink their material flows and transition, as a united front, to a circular system. All 54 of their actions were implemented by 2019.

In the 2020 European Green Deal, the new plan announced goals for the entire life cycle of the product, specifically targeting how products are designed. One of their initiatives for 2021 is to "require companies to substantiate claims they make about the environmental footprint of their products/services by using standard methods for quantifying them." This is essential for large scale adaption of the CE so that claims may be comparable across the entire board. Further, the European Commission claims that this will help buyers and investors make "more sustainable decisions". The EU has made exciting advancements, goals, and legislation in the move towards this circular system. They not only realize the need for such an economy and are trying to implement it, but have also seen the need for a way to quantify product's and company's adoption of the processes.

The Ellen MacArthur Foundation offers Circulytics, a "company-level measuring tool reveals the extent to which a company has achieved circularity across its entire operations". It doesn't just look at a specific product, it looks at the company as a whole to generate a scorecard. It can be used to evaluate the company's circular economy health and score them on indicators such as strategy, innovation, and material flows. It gives companies a comprehensive picture of their circular economy performance. This tool has been a step towards the quantification that the circular economy requires to becoming an understandable system for companies to work towards.

James Woolven from the Ellen MacArthur Foundation has discussed how measuring circular economy performance is a recently explored area and how this may lead to "incremental tweaks to linear systems rather than the adoption of truly circular business models" (Woolven, 2021). He states that the idea of the circular system and how that affects business has many interpretations, thus requiring a standardization of the concepts. Insights and Analysis Lead at the Ellen MacArthur Foundation, Jarkko Havas, says: “It is vital that we understand how to achieve a circular economy beyond the recirculation of materials. Upstream solutions such as product and service design are essential to eliminate waste before it happens."

It is clear that the need for a standardized way to evaluate company's and systems on their preference for the circular economy is needed. The Ellen MacArthur foundation has taken steps to create a tool to evaluate the company as a whole, while the European Union is working on developing a way to substantiate "green claims". What is missing from these, however, is a way for a company to have a standardized way to look at their product, their design alternatives, and competing systems.

MULTI CRITERIA DECISION MAKING METHODS AND THE ANALYTICAL HIERARCHY PROCESS

Multi criteria decision making, MCDM, is based on the fact that difficult or complex decisions may be made through obtaining and assigning weights to different criteria (Aruldoss, 2013). In doing so, the “best” alternative may be quantified and presented. As more criteria are introduced into a problem, it becomes more complex. The criteria may also have different levels of importance in the final objective, further increasing the complexity. It is necessary, then, to employ a methodology to assist in these complex decisions or determination of the best alternative. In the article by Aruldoss et al., these MCDM methods are presented and their benefits and flaws are discussed.

The analytical hierarchy process, AHP, decomposes the problem into a systematic hierarchy procedure. The decision maker must break down the problem into the following elements: overall project goal, criteria, sub-criteria, and alternatives. The project goal is the main objective of the problem. The criteria are more general, overarching goals that make up the project goal. Each criteria may have sub-criteria: more detailed and focused goals. Lastly, the bottom of the hierarchy consists of the alternatives considered. The process allows the user to make an informed decision which alternative aligns the closest with their goals and criteria.

Utilizing pair-wise comparison matrices, the relative importance or priorities of different criteria can be obtained. These pair-wise comparisons determine the magnitude of importance of one element over another. This method has its strengths in that it “is not capable of reflecting human’s vague thoughts” (Aruldoss, 2013) and contains inherit checks on inconsistencies. The validity and efficacy of the AHP process has been demonstrated by Saaty (1980).

CASE STUDIES

Green Buildings Case Study Analysis Using AHP and MAUT in Sustainability and Costs

Authors Ryan Doczy and Yassir Abdel Razig noted the importance of developing methodologies capable of assisting designers and architects in assessing the sustainability of their projects (Doczy et al., 2017). They proposed a model that combines the analytical hierarchy process with the multiple attribute utility theory (MAUT) in order to define the objectives of a project and use weights to prioritize specific goals. It allowed them to utilize their proposed model and identify the "superior alternative" given the projects criteria. Their methodology was successful and had several benefits. First, it allows the decision making process to be streamlined by showing how the alternatives meet the overall and individual goals. Second, it alerted the decision maker to areas where alternatives could perform better or be further modified to meet the specified goals. Last, it allowed the user of the methodology to control the criteria and sub-criteria in the model to better fit their overall goal.

Sustainability assessment of flooring systems in the city of Tehran: An AHP-based life cycle analysis

In a study by Reza, Sadiq, and Hewage (Hewage et al., 2011), a framework of an analytical hierarchy process and LCA assisted in the decision making of a sustainable flooring system. They considered three alternatives: concrete, clay, and polystyrene blocks. In the AHP analysis, they chose environmental, economic, and sociopolitical sustainability factors as the criteria, each with several sub-criteria. The study used this methodology to define the relative weights of the criteria and sub-criteria at their respective hierarchal levels. They noted that their model is flexible and could be changed depending on the scope or the focus of the study.

"Authors believe that the AHP-based LCA for building systems assists decision makers to find sustainable alternatives among available options and promises a more sustainable product or process" (Hewage et al., 2011). Similarly, this method is beneficial in denoting the *less sustainable options*. When comparing alternatives, it is important to recognize the both the highs and the lows and where concepts are falling short of meeting goals and expectations. In doing so, suggestions and improvements can be made.

Integration of ECQFD, TRIZ, and AHP for innovative and sustainable product development

The authors of this article utilized several methodologies to make assist in making the optimal decision for innovation and sustainability for an automotive component (Vinodh et al., 2014). They began by selecting the automotive component then integrating a ECQFD-TRIZ-AHP design approach. In this study, they utilized methodologies to develop several different alternatives, then they used the analytical hierarchy process to choose the best alternative of their different concepts.

From these case studies, the use of the analytical hierarchy process in making decisions regarding sustainability has been validated. The benefit lies in creating the hierarchal system with the overall goal, sub-criteria, and alternatives. It allows the best decision to be clearly and empirically shown. This methodology has been used both in comparing different design alternatives that the user has created and by comparing competing designs.

SUSTAINABLE MINDS SOFTWARE

In this study, the sustainability report was generated through the Sustainable Minds Software. The SM 2013 Impact methodology "is a life cycle assessment methodology for evaluating potential ecological and human health impacts from products used in North America. The science and data is from trusted sources including the U.S. Environmental

Protection Agency (EPA) and the National Institute for Standards and Technology (NIST)." By inputting the materials, weights, manufacturing processes, and life cycle factors for all of the components in a concept, a scorecard is generated.

The software requires the system bill of materials (SBOM) for the whole product system of each concept. It then multiplies the specific chemical emissions by the inputs of the SBOM to generate the pollution of the system. The SM Methodology utilizes Tool for Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) developed by the EPA to convert the inventory emissions into environmental impacts. The next step of the methodology is to normalize impacts. This software utilizes the total environmental impact in the United States in 2008 as the reference. The impact factors are presented in millipoints (mPt - a standardized unit for the concept's impact shown as the share of one American's annual environmental load) and CO_2 equivalents. In this study, I will be looking specifically at the impacts by SBOM inputs that the software generates for each concept. An example of the concepts and their generated functional scores and points is shown in Figure 2.

	Impacts / functional unit mPts/func unit	CO_2 eq. kg / functional unit CO_2 eq. kg/func unit	Performance improvement from reference mPts	Performance improvement from reference %	Units of svc delivered Svc. Units	Assessment type
Reference black crows Copy Declare as: | Final	0.041	0.28			10	Estimate
Lowest impact soulpoles Copy | Delete Declare as: Reference | Final	0.0022	0.034	+0.039	+95%	10	Estimate
Kang Poles Copy | Delete Declare as: Reference | Final	0.0054	0.066	+0.036	+87%	10	Estimate
vita Copy | Delete Declare as: Reference | Final	0.0073	0.072	+0.034	+82%	10	Estimate

Figure 2. Sustainable Minds Concept Comparison

TERMINOLOGY

Analytical Hierarchy Process

"The Analytic Hierarchy Process (AHP) is a general theory of measurement. It is used to derive ratio scales from both discrete and continuous paired comparisons. These comparisons may be taken from actual measurements or from a fundamental scale which reflects the relative strength of preferences and feeling" (Saaty, 1980).

Circular Economy

"A circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources" (Ellen MacArthur Foundation)

Life Cycle Assessment

"A method used to evaluate the environmental impact of a product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal" (Ilgin & Gupta, 2010).

Modularization

"Decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific strategies" (Ericsson & Erixon, 1999)

Multi-Criteria Decision Making Methods

"Help decision makers learn about the problem situation, about their own and others values and judgements, and through organization, synthesis and appropriate presentation of information to guide them in identifying, often through extensive discussion, a preferred course of action. The process leads to better considered, justifiable and explainable decisions – the analysis provides an audit trail for a decision" (Belton & Stewart, 2002).

Product Modularity

"Defined as having two characteristics: 1) similarity between the physical and functional architecture of the design, and 2) minimization of the degree of interaction between physical components" (Ericsson & Erixon, 1999)

Recyclability

The ability, ease, and likelihood of a product to be recycled. Dependent on how easy each material is to isolate and local recycling capabilities.

Repairability

The ease of repairing a product. Dependent upon availability of repair documentation, ability to access all parts of the product, ease of disassembly, and part availability if needed.

Reusability

The ability of a product to be reused. In this paper and study, it is dependent on company end of life management, ability to make upgrades or repairs, and ease of remanufacturing or refurbishment.

3 Proposed Method

3.1 INTRODUCTION

Multi Criteria Decision Making (MCDM) allows different systems or concepts to be ranked against each other with a standard approach. MCDM methods have shown efficacy in determine the best optimal solution for a complex problem given a set of criteria. Within MCDM, the Analytical Hierarchy Process was chosen. The Analytical Hierarchy Process (AHP) is capable of dealing with multiple criteria simultaneously (Saaty, 1980). This MCDM methodology was chosen in order to compare different systems using multiple criteria to create an overall ranking.

With complex problems, it is important to review and define all the criteria and give them a priority (importance) of that particular objective in order to rank them against each other for each system. In this system, the objective is to determine which system is the most fit for the circular economy, and the factors include repairability, reusability, recyclability, and sustainability. Using a series of pair-wise comparison matrices, these priorities can be normalized and used in the final ranking of the systems. The structure of the AHP process is shown in Figure 3.

As discussed in the Literature Review, the Ellen MacArthur Foundation and the European Circular Economy Action Plan have seen the need to measure a product's or company's circularity. This is necessary in order to substantiate claims made that a product is "green". Circulytics, the tool from the Ellen MacArthur Foundation, is able to give the *entire company* a score card on their performance in the Circular Economy. Though very beneficial to see how the company is doing overall, the benefit to the proposed method in this paper, however, is that it allows multiple design alternatives to simultaneously be compared and the superior alternative to be revealed. This means that a company can use the methodology when comparing several of their own design alternatives, or it can be used to prove that a company's specific product is superior (in terms of the circular economy) to competing systems.

Another benefit to this methodology is allowing the user to see where their system has flaw. By utilizing the score sheet to develop the alternative priorities, they can see where each system is lacking. Thus, alterations to their design may be made and their overall score adjusted.

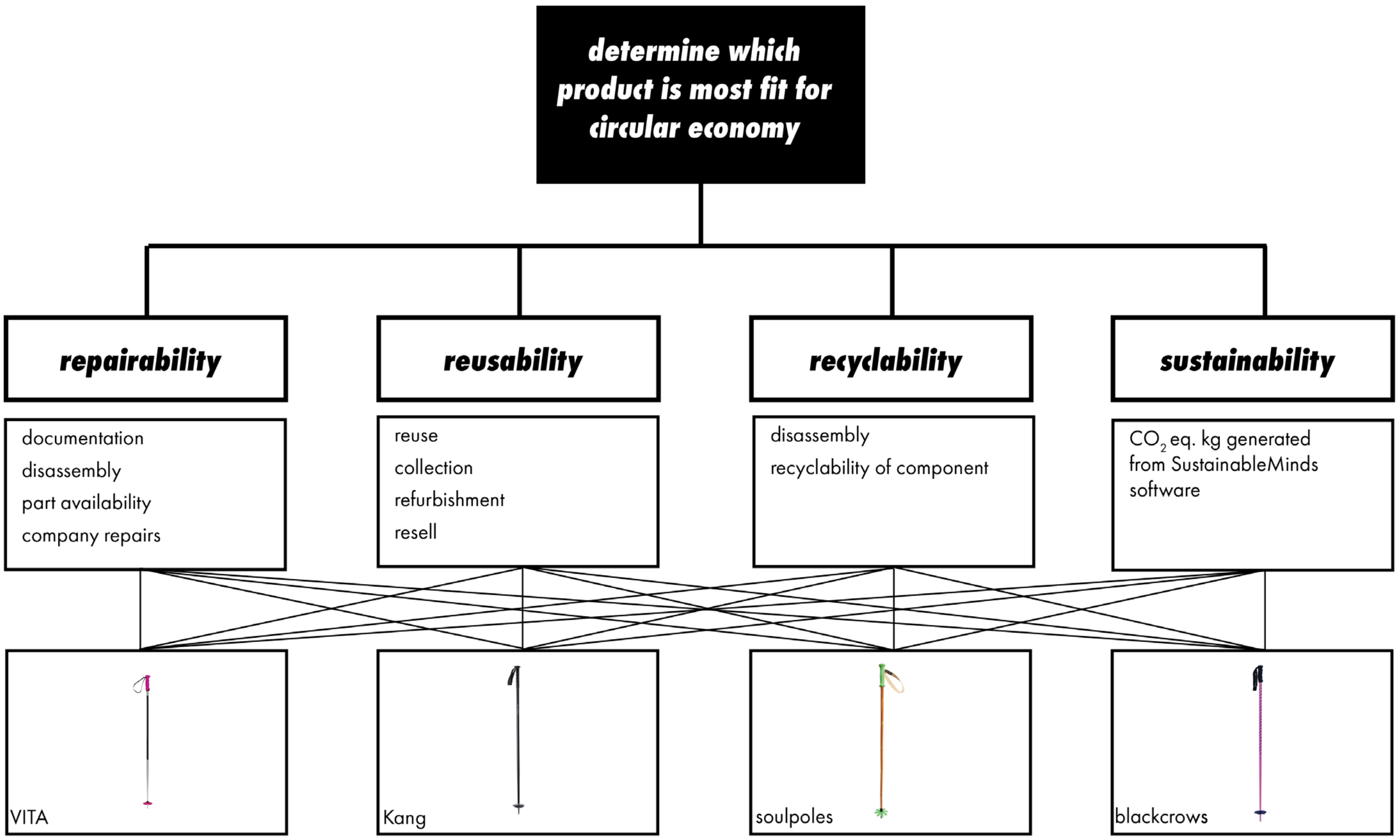

Figure 3. AHP Structure

3.2 FACTOR PRIORITIES

In determining whether or not a product is fit for the circular economy, four factors were chosen: repairability, reusability, recyclability, and sustainability of materials. Each of these factors are critical in the product's design and must be considered from the early conception of the idea so that product truly fits into the circular economy. Each of these factors were given a priority weight. These priority weights were chosen subjectively based on the understanding of the CE and importance of the factors, but treated consistently throughout the methodology. These factors and their scores are shown in Table 2.

Table 2. Prioritized list of factors	
factor	**priority**
repairability	10
reusability	8
recyclability	7
sustainability of materials	5

1: repairability (10)

The ability to make repairs to the entire system by replacing or repairing broken component in order to prolong the lifespan

A very high priority was assigned to repairability due one of the most important characteristics of the circular economy - extending the life of the product.

2: reuse and refurbishment (8)

The product may be reused multiple times in its original form by a second user or may have components replaced by company and resold as a refurbished product.

A high priority was assigned to reuse to reflect the importance of extending the life of the product and reintroducing the product to the market

3: recyclability (7)

Breaking down the system into its recyclable, component parts and allowing them to be remade into new products.

Assigned a moderately high priority (7) to reflect importance of end of life management and keeping the materials in the economy for as long as possible. It was not given as high of a priority as repairability or reuse so that the methodology is focused extending products life, not on disposal.

4: sustainability of materials (5)

The sustainability of the chosen materials in terms of carbon footprint (CO_2 eq. kg) as determined by sustainability software (Sustainable Minds)

Sustainability of materials is assigned a moderate priority (5) because the focus of the circular economy is keeping the value associated with the materials as long as possible, more so than the actual carbon emissions of each.

Using a standard pair-wise comparison matrix, Table 3., a criteria weight vector {W} is developed, Table 4. This vector will be used in the final calculation of the options. The next step is to quantitatively score each system for each factor using the methods below (sections 3.3 to 3.6). This generates an alternative priority vector for each factor using pair-wise comparison matrices. These vectors, along with the criteria weight vector {W}, will be used in the final step to rank each system based on their scores and the original priorities.

Table 3. Standard Pair-Wise Comparison Matrix

	10-8	8	8-6	6	6-4	4	4-2	2	2-0
10-8	1	2	3	4	5	6	7	8	9
8	1/2	1	2	3	4	5	6	7	8
8-6	1/3	1/2	1	2	3	4	5	6	7
6	1/4	1/3	1/2	1	2	3	4	5	6
6-4	1/5	1/4	1/3	1/2	1	2	3	4	5
4	1/6	1/5	1/4	1/3	1/2	1	2	3	4
4-2	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
2	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
2-0	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1

Table 4. Standard Pair-Wise Comparison Values and Weight {W}

	repairability (10)	reusability (8)	recyclability (7)	sustainability (5)	{W}
repairability (10)	1	2	3	5	0.555
reusability (8)	1/2	1	2	4	0.252
recyclability (7)	1/3	1/2	1	3	0.097
sustainability (5)	1/5	1/4	1/3	1	0.097

3.3 REPAIRABILITY *(10)*

Several factors play a role in determining whether a product is repairable or not. First, does the company offer replacement parts? In the case study of ski poles, the four main components must be offered (shaft, grip, strap, and basket). Baskets are more widely offered, but other components are often never sold by the company. Even if the user was very interested in repair and was able to find the component online, it would have to be compatible with the dimensions of the rest of the system. For example, if the shaft needed to be replaced, it would have to have the same diameter of the hole for the grip (pole shafts often vary in size), and it would have to have the same connection for the grip. Further, are the spare components offered proprietary parts or are they something that the consumer can find elsewhere? In this case study, proprietary parts will not commonly be found because currently, very few parts of ski poles are offered separately; however, the use of common types of fasteners readily available to the consumer is something to consider.

Second, the fasteners used to assemble the entire system will dictate how repairable the system is. Epoxy creates difficulty when trying to remove a specific component. Further, the consumer would need to re-epoxy the part to put the system back together. In a case study of ski poles, nearly all of the components of poles currently on the market are epoxied together. If the user was trying to replace a grip, they would first have to remove the epoxied grip from the shaft, then re-epoxy the grip back on the shaft. If the system used a mechanical fastener rather than a permanent solution like epoxy, the fasteners used should only require tools commonly found. If the number of fasteners increases, so will the difficulty of repair. Whether or not the company provides the consumer with easily accessible repair instructions also will determine the repairability of the system. The score sheet in Table 5. is used in this study to quantify the repairability of each of the four different systems considered:

Table 5. Repairability Score Sheet

repairability index for __________			
criteria	**sub-criteria**	**score**	**weighted score**
documentation	*does a repair manual or guide exist?*	0 /1	0 /10
disassembly 0 = cannot be replaced 1= epoxied on 2 = requires proprietary tools 3 = requires basic tools 4 = requires no tools	*how easy it the system to disassembly?*		
	strap	/4	
	grip	/4	
	shaft	/4	
	basket	/4	
		0 /16	0 /20
part availability 0 = no, 1 = yes	*are new parts offered?*		
	strap	/1	
	grip	/1	
	shaft	/1	
	basket	/1	
		0 /4	0 /50
company repairs 0 = no, 1 = yes	*does the company offer a warranty or repairs?*	0 /1	0 /20
			0 /100
			0 /10

3.4 REUSABILITY

Reusability looks at how and if the system is reused. When the consumer decides they want a new system may not necessarily be the end of the product's or material's useful life. That system may still be resold and reused by others, sometimes requiring upgrades or repairs to the system. In the case study of ski poles, all unbroken poles may be resold and reused. Whether or not the system is reused is dependent upon the users, the company's system design, and the ability to complete necessary upgrades.

Many consumers may not go through the steps necessary to keep the product in life for as long as it should be (repairs, reselling, etc...) and may opt for the convenience of throwing them away. The company should aim to make this process of reuse as easy as possible. With VITA, the company will recollect the old poles by offering an incentive to those purchasing a new pair. In doing so, they are keeping the product from entering the landfill. VITA may then do any necessary upgrades (replace strap if wearing out, baskets if broken, etc...). These lightly used or refurbished poles may then be resold by the company for a lower price than a new set.

The quantification of this factor takes into account how the company deals with the end of life management and how easy the product is to update (disassemble and reassemble). The score sheet for this factor is shown in Table 6.

Table 6. Reusability Score Sheet

reusability index for _________			
criteria	**sub-criteria**	**score**	**weighted score**
reuse 0 = no, 1 = yes	*can the poles be reused, resold, or donated?*	/1	0 /30
collection	*are the old poles and parts collected by company*	/1	0 /20
refurbish/remanufacture 0 = cannot be replaced 1= epoxied on 2 = requires proprietary tools 3 = requires basic tools 4 = requires no tools	*can broken/old parts be updated?*		
	strap	/4	
	grip	/4	
	shaft	/4	
	basket	/4	
		0 /16	0 /30
resell 0 = no, 1 = yes	*are old or refurbished poles resold by the company?*	/2	0 /20
			0 /100
			0 /10

3.5 RECYCLABILITY

Whether or not a product is recyclable is an important factor in the circular economy. In order to maximize the value associated with each material for as long as possible, each component must be able to be recycled at the end of the its useful life. This score is calculated by with two sub factors: the recyclability of each component and the ease of disassembly of the entire system.

Choosing materials that are widely accepted at recycling centers is an important consideration in order to facilitate the act of recycling on the users. The scoring of this sub-criteria is as follows: 0 - not recyclable, 1 - limited, 2 - widely accepted. Further, the system must be easy to break down into the component materials. The score sheet for this system is shown in Table 7.

Right now, this score sheet deals with whether or not the materials are recyclable and how easy they are to isolate. It would be a beneficial advancement in the future to add in the environmental impact of recycling each component. For example, recycling the aluminum shaft may have a vastly different load on the environment than recycling the basket. In adding this analysis to the methodology, a more holistic picture of the impact of the full LCA could be realized.

Table 7. Recyclability Score Sheet

recyclability index for ________

criteria	sub-criteria	score	weighted score
disassembly	*can each piece be isolated?*		
0 = cannot be replaced	strap	/4	
1= epoxied on	grip	/4	
2 = requires proprietary tools	shaft	/4	
3 = requires basic tools	basket	/4	
4 = requires no tools		0 /16	0 /30
recyclability	*is each component recyclable?*		
0 = not recyclable	strap	0 /2	
1= limited	grip	0 /2	
2 = widely	shaft	0 /2	
	basket	0 /2	
		0 /8	0 /70
			0 /100
			0 /10

3.6 SUSTAINABILITY

The sustainability of the materials is something that must be considered in every “sustainable system”. This criteria is the foundation for a green product. Though in this circular economy ranking methodology that I am developing focuses more on the importance of keeping the product in use for as long as possible, it is impossible to ignore the impact made by the materials and manufacturing choices. Sustainable Minds is the software chosen to create obtain these values. By inputting each material, the weight, and the manufacturing process, the system's CO_2 eq. kg can be generated. This software is limited though in that not all materials are available. Some newer materials are lacking from the database. As time goes on, however, I expect these materials to gain more popularity and the database to include more options.

In the AHP methodology being used, a vector of the alternative priorities is needed on a scale of 0 - 10. Because the value generated is the system's CO_2 eq. kg, a normalizing equation was developed to create this vector.

$$z_i = 10 - \frac{(x_i)(10)}{\max(x)}$$

where:

z_i = the ith normalized value

x_i = the ith value

max(x) = the maximum value

3.7 FINAL RANKING SYSTEM

The final steps of the process are to create a Final Rating Matrix, $[F_R]$ of the criteria and the design options using the vectors developed for each factor. Transposing that matrix and multiplying it by the criteria weight vector, {W}, will produce a vector of the final ratings.

$$\{\text{final rating}\} = [F_R]\{W\}$$

From this final vector, the design option with the highest score is the one that is the most fit for the circular economy compared to the alternatives.

4 Design Approach

4.1 MODULARITY

Using the criteria developed in the CE ranking methodology, the design needs to include the following: easy repairs, able and planned for future reuse, easy to recycle, and sustainable materials. Using the input from the initial user survey, the poles need to be durable and cost effective. From these considerations, the idea of a modular ski pole was conceptualized. As defined by Ericsson and Erixon in *Controlling Design Variants: Modular Product Platforms*, the modularization of a product is "decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific strategies" (Ericsson & Erixon, 1999). By understanding this definition and understanding the role that the company's vision and mission plays into the modularity, a successful design can be developed.

The modularization of the ski poles provides several beneficial aspects. Primarily, it means that the product can be repaired. No longer does the entire system have to be thrown out when one component breaks. If the shaft were to break, the user could easily get a new part and replace it. By designing it in such a way where epoxy is not required to hold the system together, users can use basic tools to remove the components off of the shaft and replace the damaged part. Durability being the second most important factor to the customer when purchasing, however, means that this modularity can in no way compromise the system.

The modularity also means the company can offer different styles (grip shape, basket style, and color options), and the user can create their own, custom pole. The user now has the ability to pick out everything they find important from their ski style in their ski pole. Additionally, if the user wanted to change or upgrade any aspect in the future, they would be able to without having to buy a new set of poles. In the initial user survey, several respondents reported that they owned multiple pairs of ski poles for different uses (in bounds, back country, etc...). The modularity of the poles would allow the user to update.

The first connection point that was focused on was the grip attachment. This connection had to be stable, strong, and only require basic tools to take apart. It was decided that the strap could be held in place by swaging the end of the shaft. This point would then go through a hole in the strap and lock it in place. In order to attach the grip to the shaft, two systems were explored (Figure 4 and Figure 5).

Figure 4. Grip Connection System 1

Figure 5. Grip Connection System 2

Figure 6. grip connection system 1

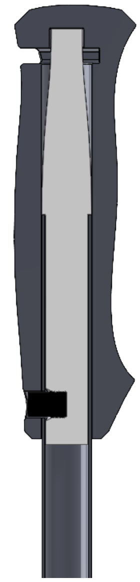

Figure 7. grip connection system 2

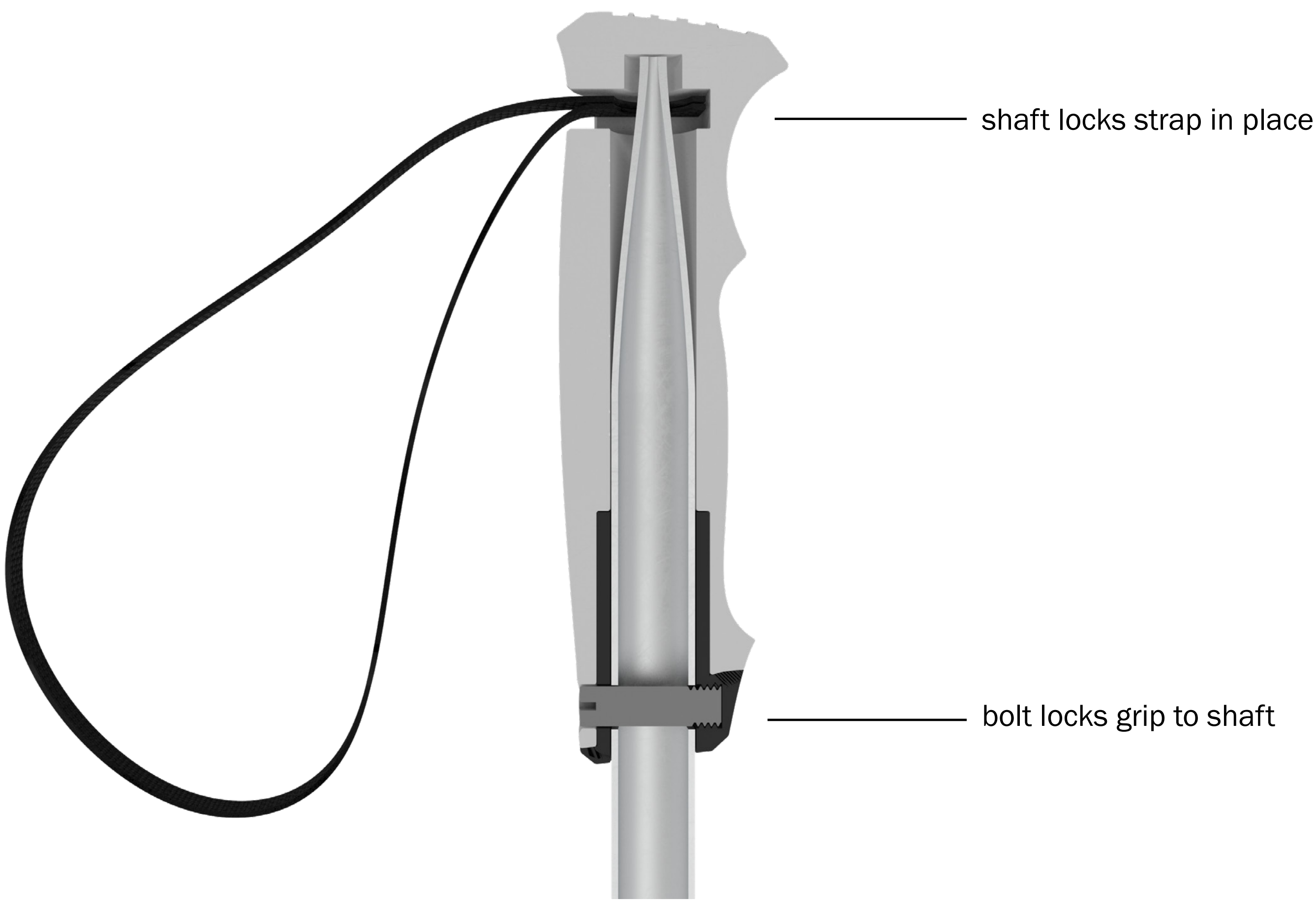

Figure 8. finalized grip concept

Because the material choice for the grip was natural rubber, a simple bolt that traveled through the grip, then shaft, then back into the grip, would not work due to the potential degradation of rubber threads. The aluminum wall thickness at that point is 0.04 inches, which would not leave enough thickness to put threads. The grip attachment first system included a small plastic collar that would go in between the grip and the shaft and provide enough thickness to create threads. The second grip attachment system utilized a “tip extension” that created the swaged end on the tip. It would travel into the center of the

Figure 9. Basket System 1

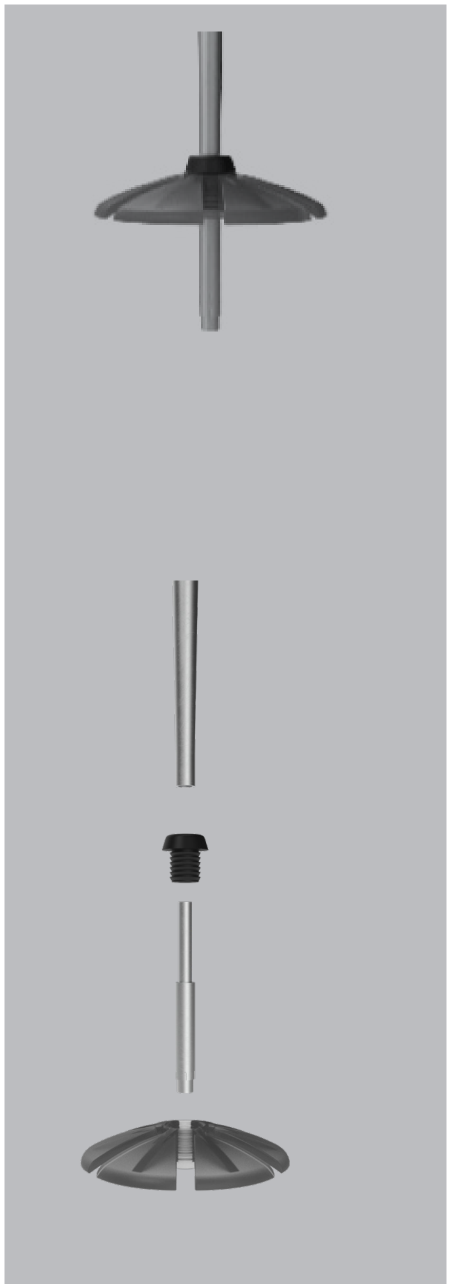

Figure 10. Basket System 2

Figure 11. Basket System 3

shaft and the hole would line up with the hole in the shaft and the hole in the grip. The bolt could then go through all three pieces and thread into the tip extension.

Grip attachment system 2 proved to be a lot trickier with user testing. Users found it difficult to line up all three holes, especially because the tip extension was completely covered inside the grip in shaft. That meant if it got out of alignment, there was no way to put it back in line. System two was significantly heavier, something that should be avoided with ski poles. Additionally, there were more steps involved in the connection. For that reason, grip connection system 1 was chosen. Figures 4 and 5 show the cross sections of each proposed system. Figure 6 shows the final part in more detail.

The next connection point to consider was the basket. Three systems were evaluated (Figures 7 - 9).

Basket system 1 consisted of a basket that slid onto the shaft till a certain point and then a customized nut screwed onto the shaft and kept the basket in place. This system, though simple, would not work due to manufacturing reasons. Additionally, there is concern that the nut would loosen over time and create a risk that the basket could be lost.

In both basket system 2 and 3, the basket stayed on through a friction fit between the TPU of the basket and the PET of the attachment piece. System 2 had the entire tip screw on and off and sandwich the attachment point. This system would require an additional aluminum piece and added unnecessary complexity. Further, there were concerns about the integrity of the tip by breaking into two different pieces. System 3 required no alterations to the shaft, save for a small hole for a pin to go through. The pin would travel through the attachment piece and through the shaft, keeping it in position. The basket would then cover up this connection point, so there wouldn't be concerns of the pin falling out. System 3 maintained the integrity of the pole the best, and there were no threaded pieces that loosen over time. For this reason, that system was chosen.

4.2 COMPANY SYSTEM DESIGN

Much of this system revolves around the system design of the company itself. The company plays an important role in extending the products life and assisting in the end of life management (Figures 13 to 18).

The company is based on a "build-your-own-pole-model". As previously stated, one of the benefits of this modular design is that it allows the consumers to have the freedom of choosing exactly what they want. As the consumer gets onto the website to order the poles (future advancement for in a ski shop), they go through a series of pages building out their pole. The basket, shaft, and grip are offered in five different swatches: black, light grey, blue, yellow, and pink. The grip is offered in an ergonomic grip and a slim grip. The basket is offered in a standard and powder style (Figure 19).

In addition to selling the ski poles, the company must also offer spare parts. If a consumer breaks the shaft of the pole, there is virtually no way they can begin to replace that part. Not only does providing these spare parts fit into the circular economy model, but it is also a form of cost savings for the consumer. They now only have to replace a single component rather than an entire set of poles.

An incentive program to get the broken pole or component back will allow the company to continue to realize that materials worth, while also encouraging the consumers to do something with their product other than throw it away. Further, a trade in program for those who want to completely update their set would allow the company to receive old poles that they may refurbish and resell while the consumer gets a discount on a new pair. The company may then refurbish and resell the poles as a used product or, for the truly broken components, responsibly recycle the materials and keep the loop closed.

This circular economy would benefit the customers, the company, and the environment. Customers will have more value associated with their ski poles because they picked out all the components, making them more personal. Ideally, this will cause them to care more about their poles and make them more likely to repair rather than replace. Customers can save money by replacing only what is broken, or take advantage of the trade in program to get a discount on a new set. This in turn creates customer loyalty for the company as the customers must come back tin order to take advantage of the trade-in and incentive program or to replace components. The company has also opened up a secondary market for themselves in which they may resell the refurbished poles.

A diagram of this circular economy system is shown in Figure 12.

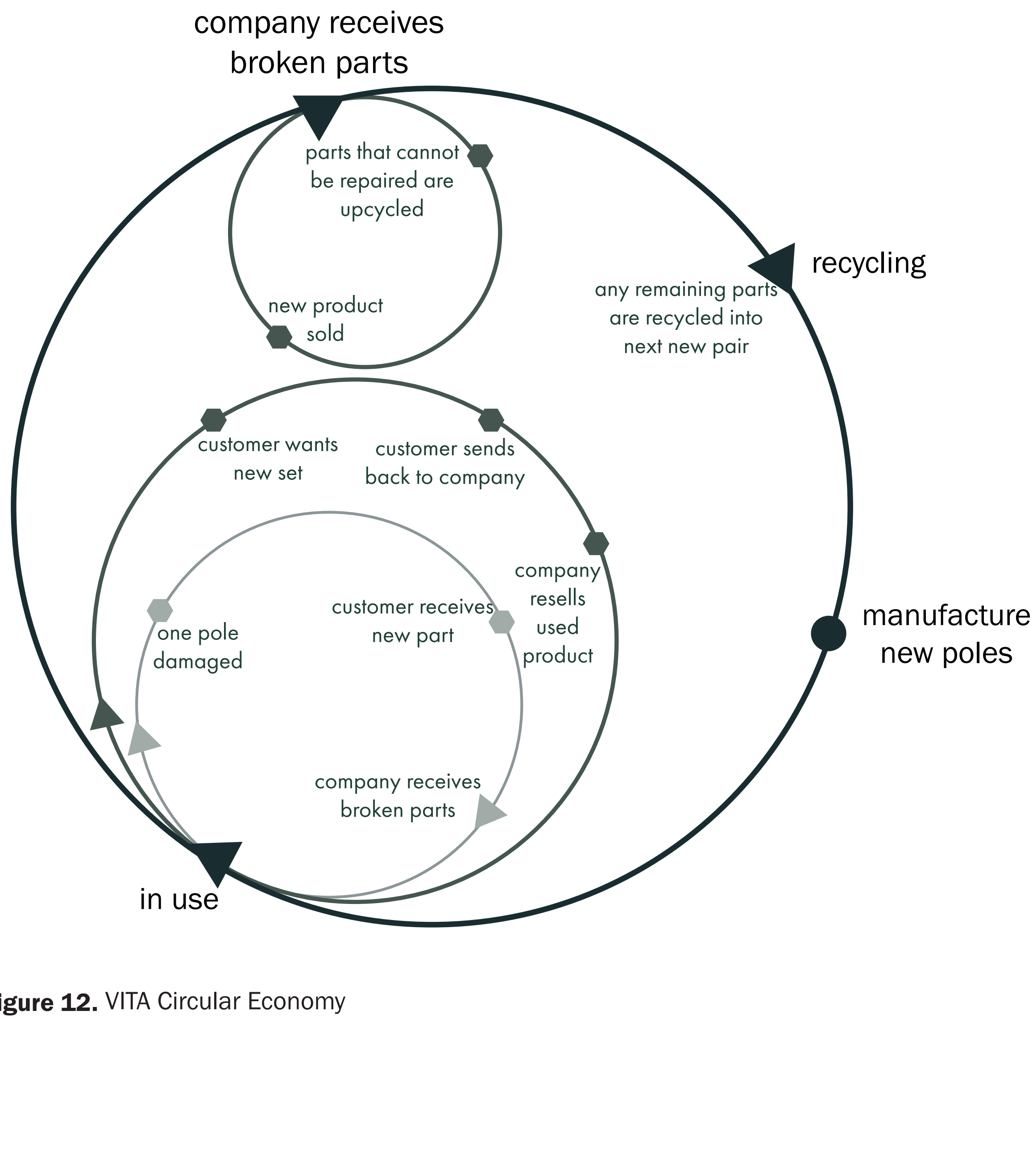

Figure 12. VITA Circular Economy

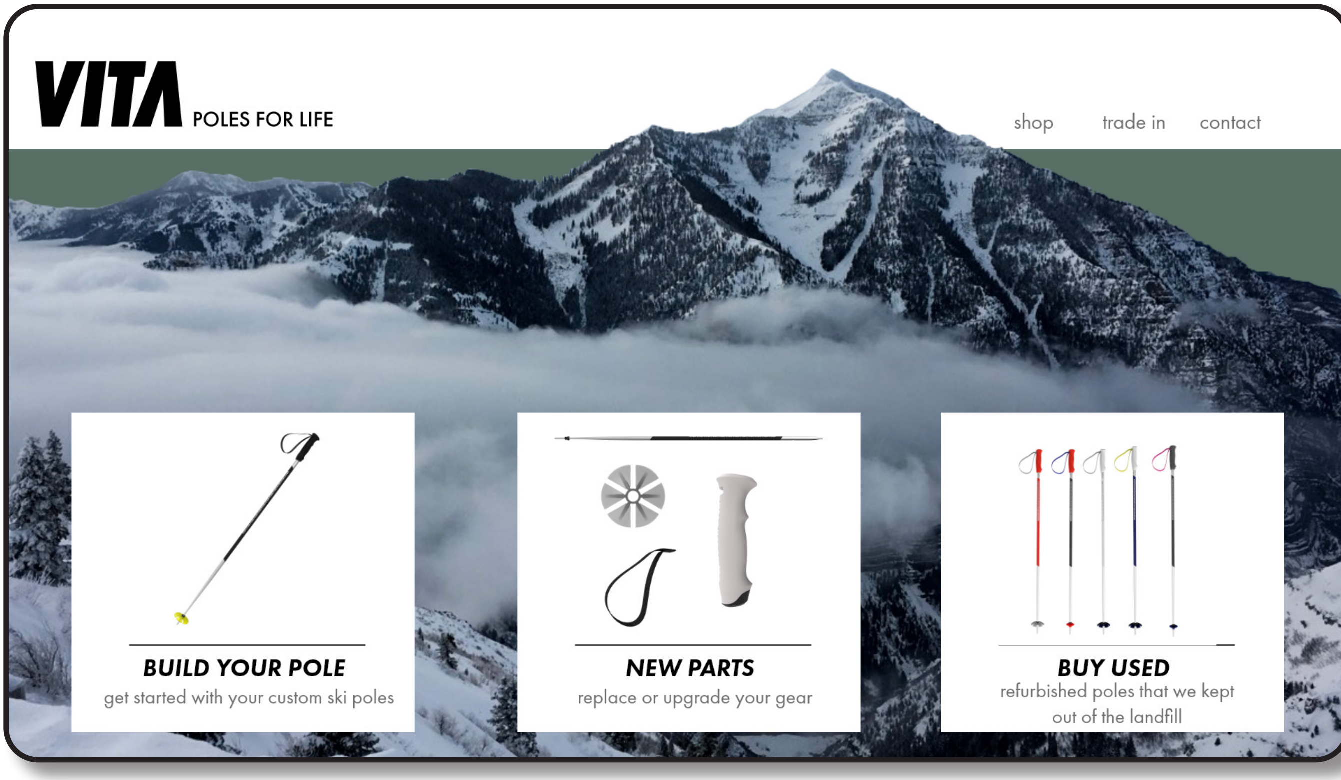

Figure 13. VITA Landing Page

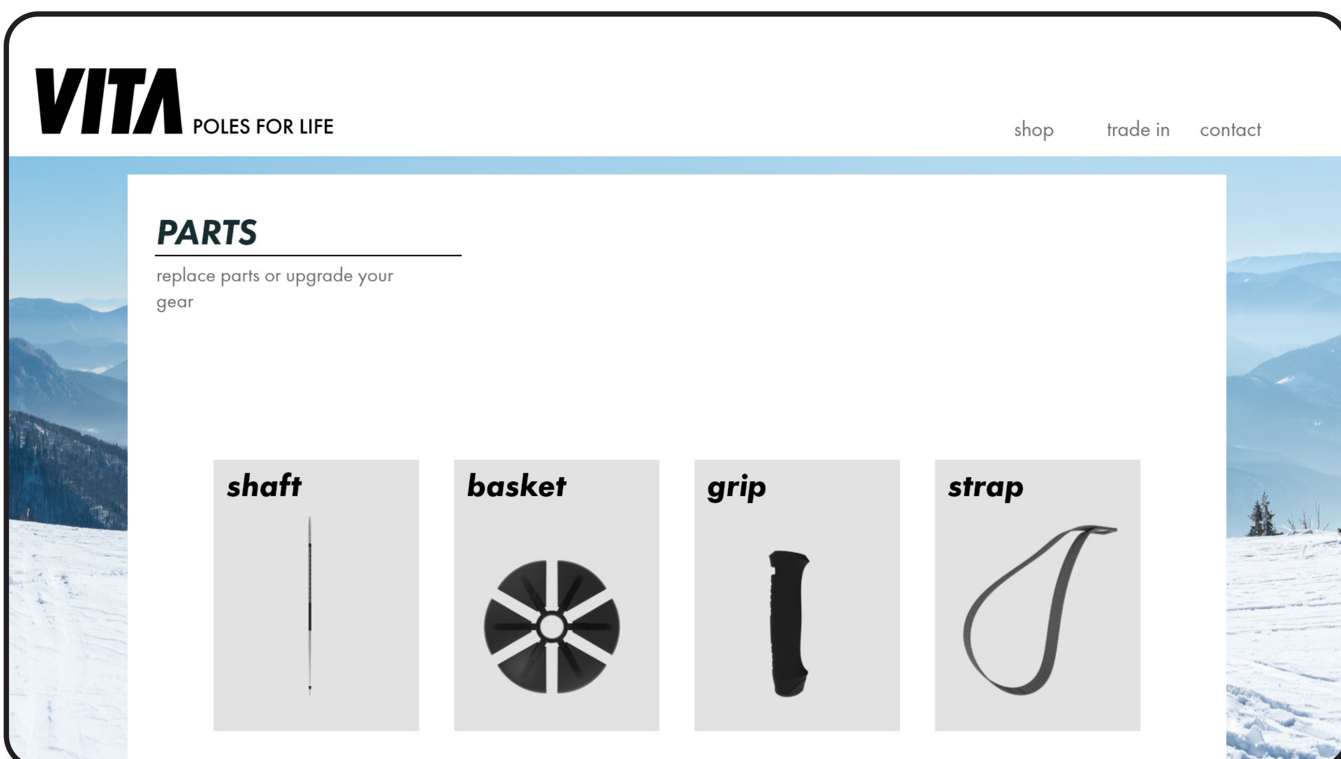

Figure 14. New Parts Page

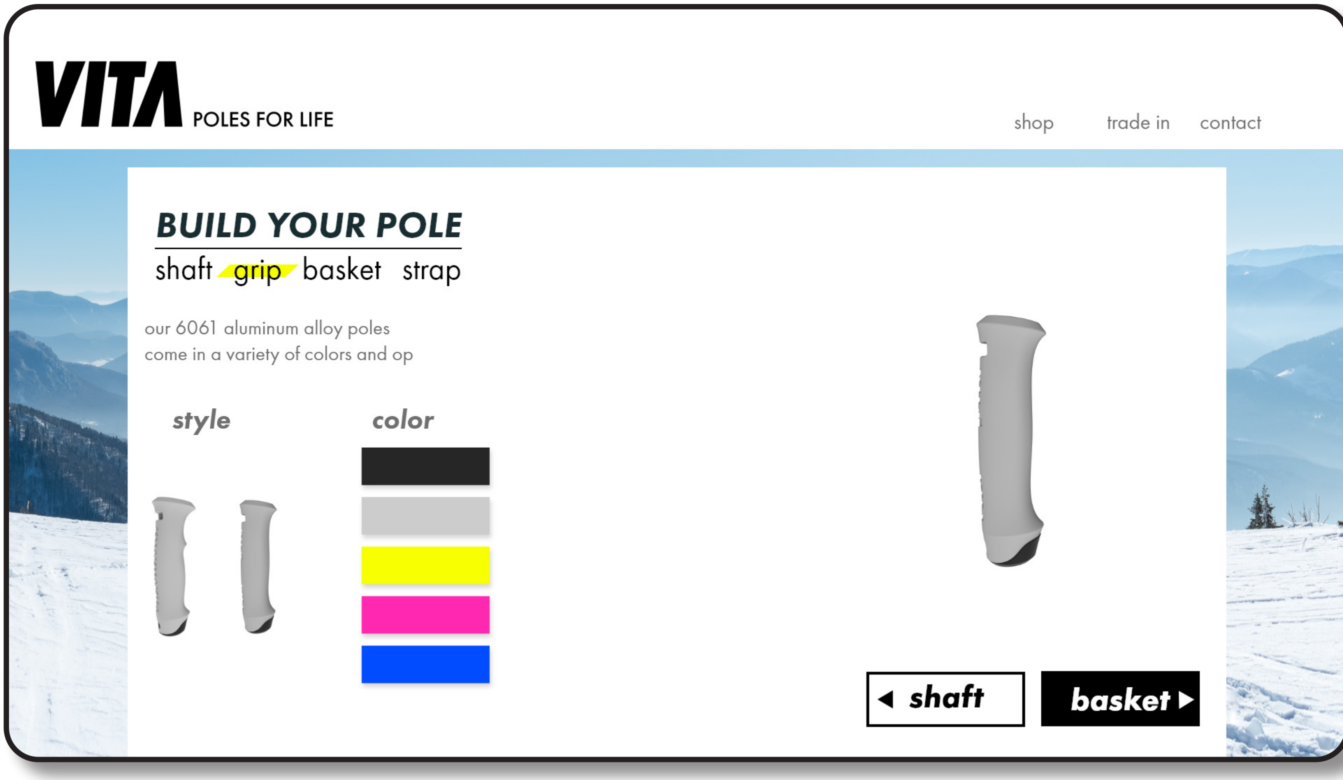

Figure 15. Pole Builder

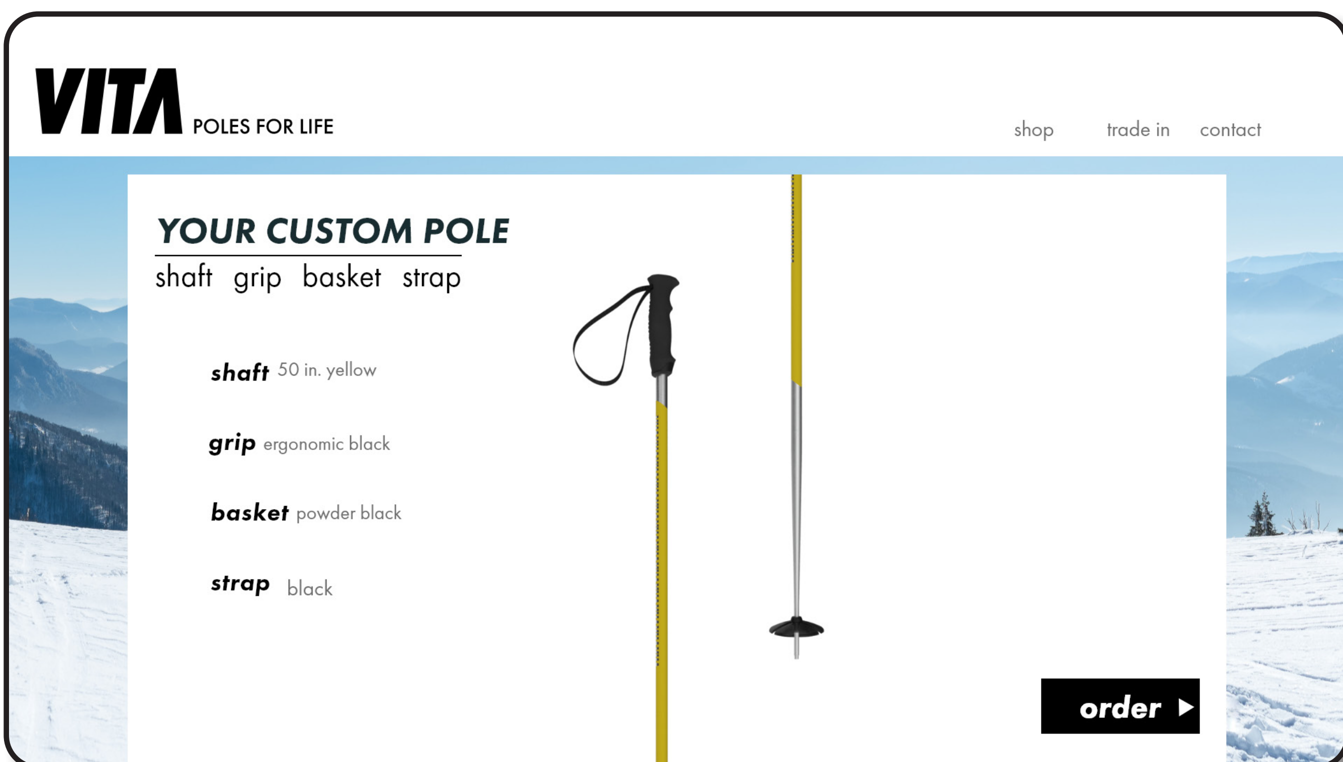

Figure 16. Custom Pole Selection

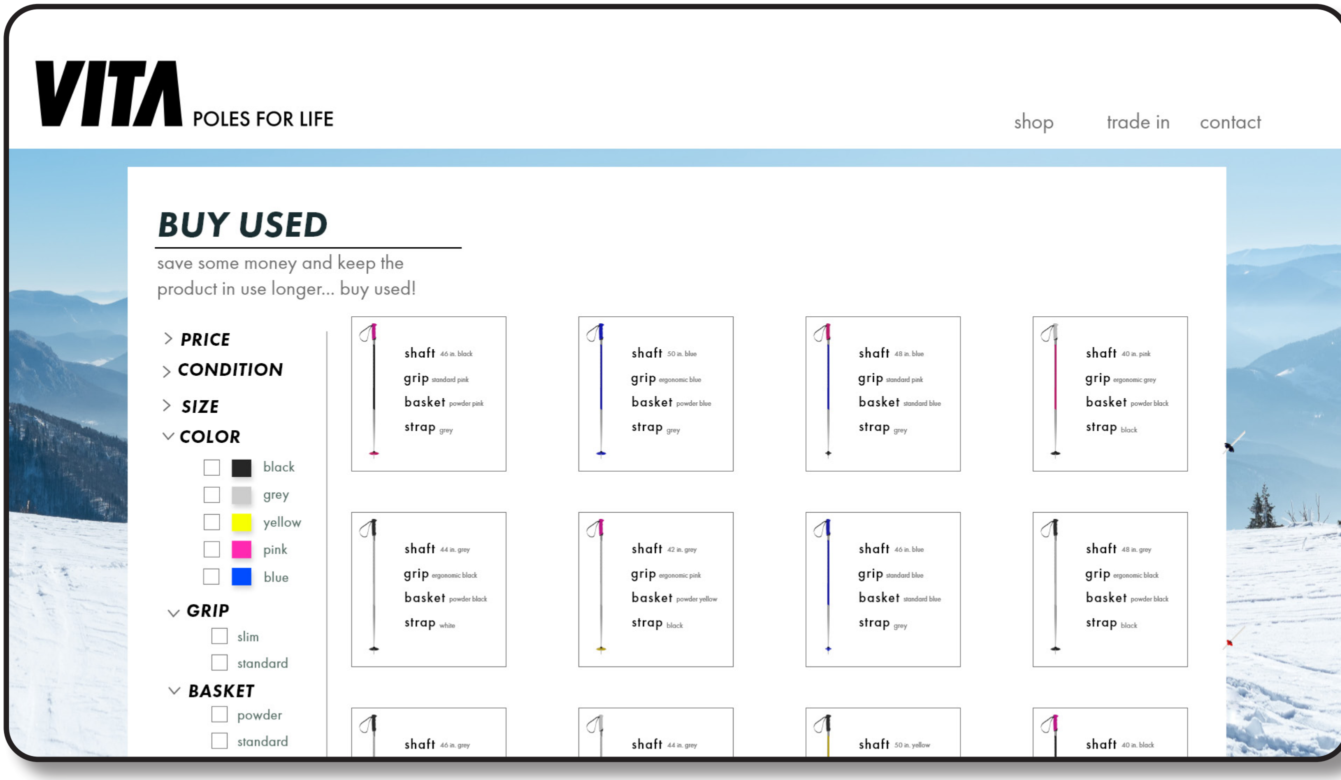

Figure 17. Used Poles

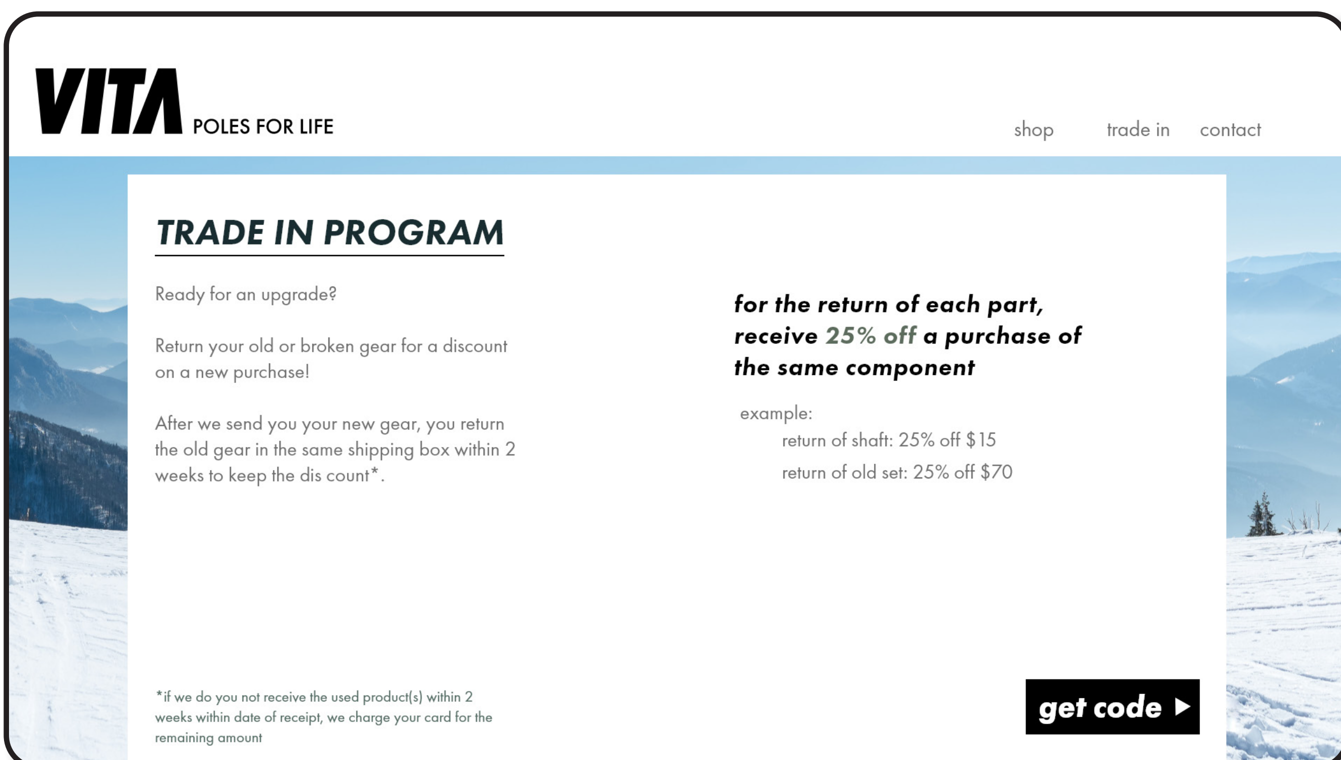

Figure 18. Incentive Program

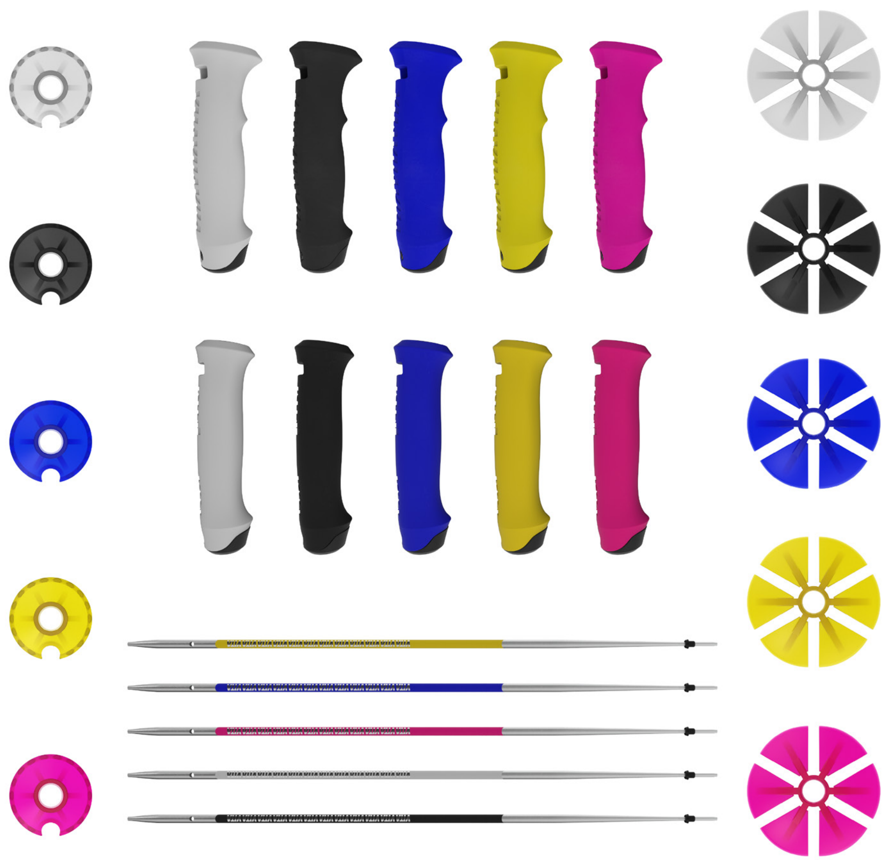

Figure 19. Pole Options

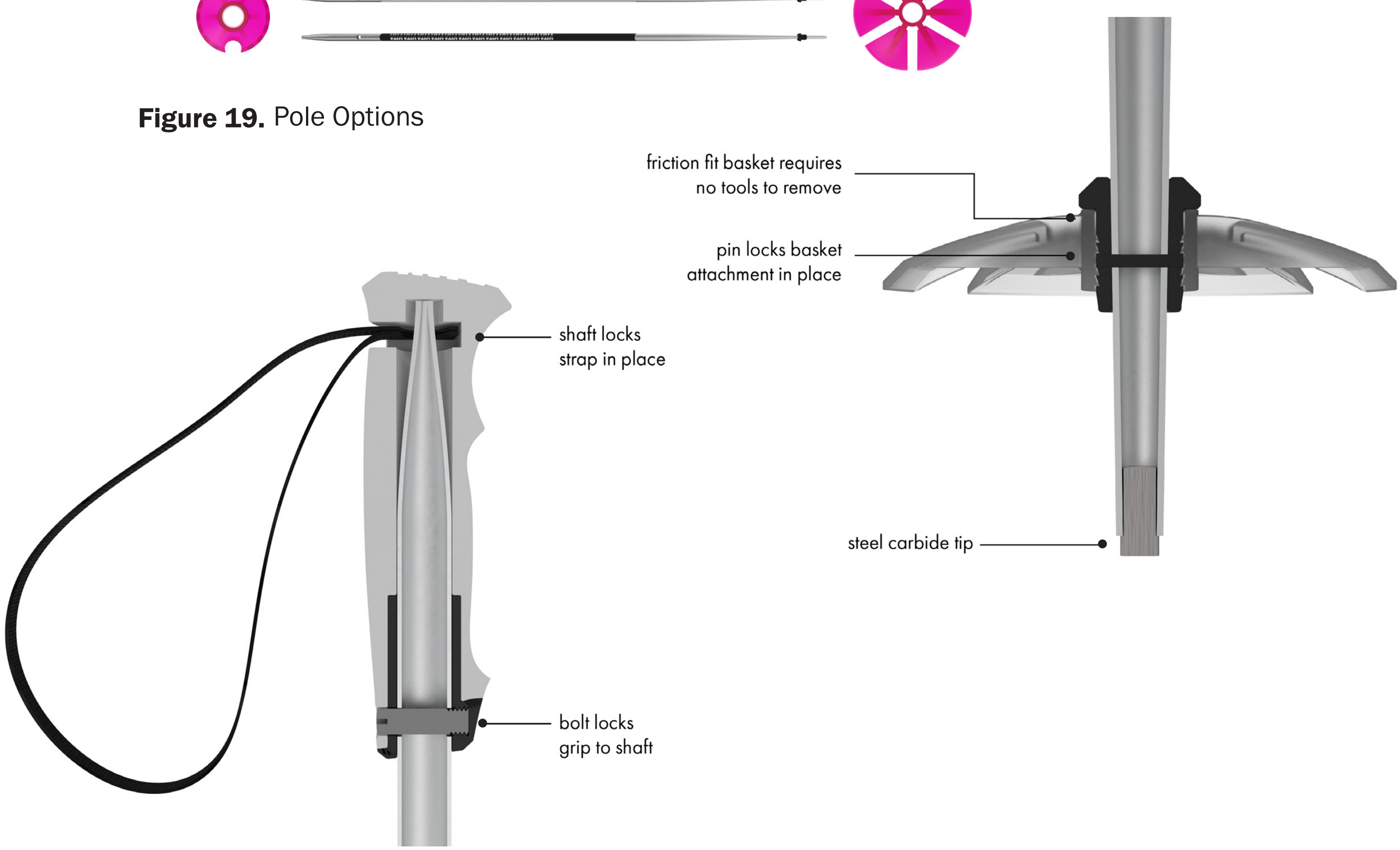

Figure 20. Pole Interfaces

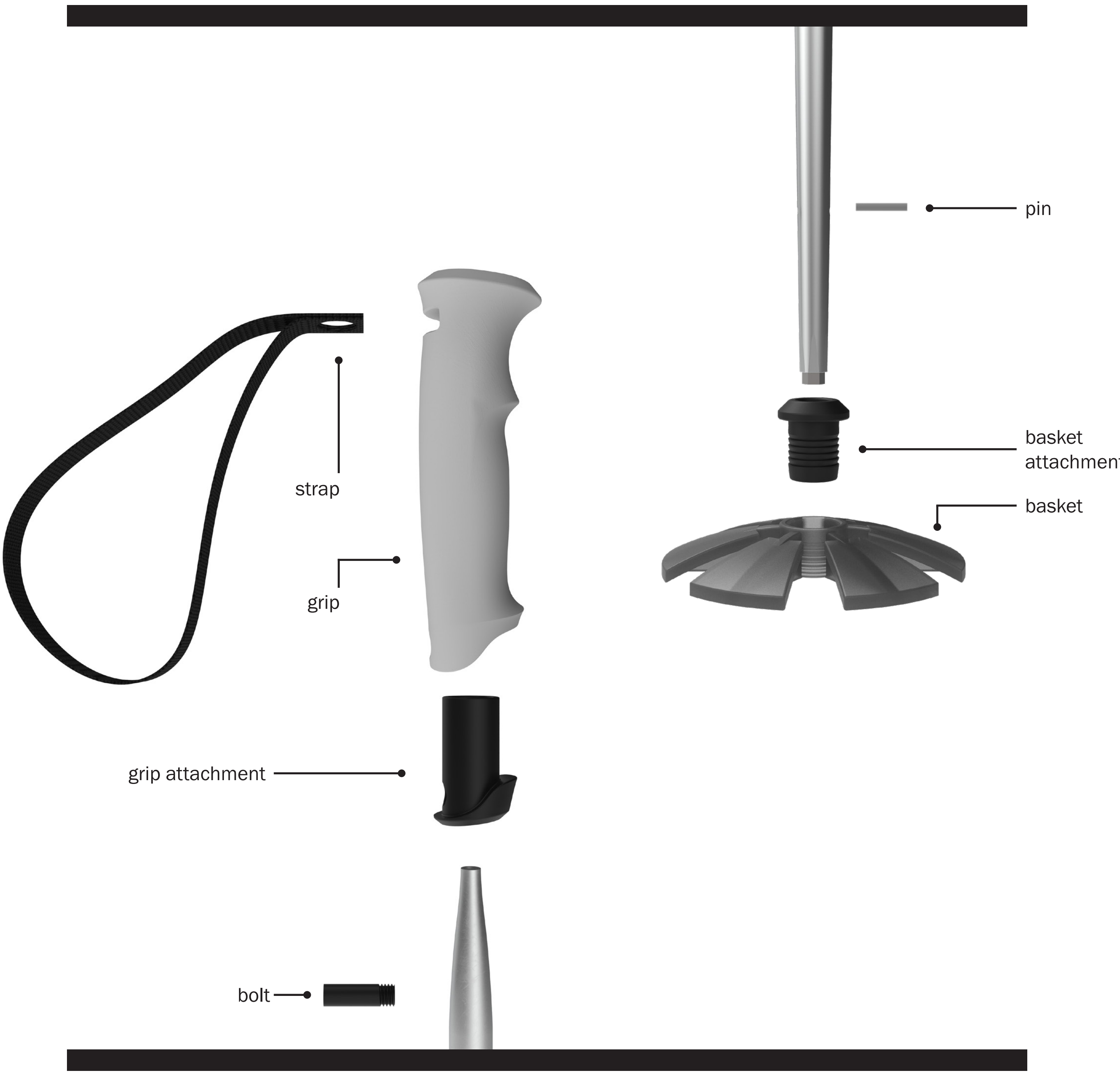

Figure 21. Exploded Views

Figure 22. Tip

Figure 23. Grip

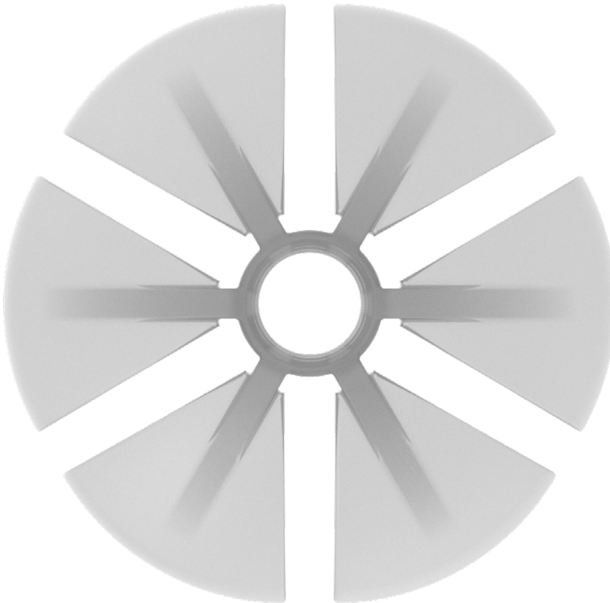

Figure 24. Powder Basket

Figure 25. Standard Basket

Figure 26. Ergonomic Grip

Figure 27. Slim Grip

one pole = 4 parts

replace components as needed

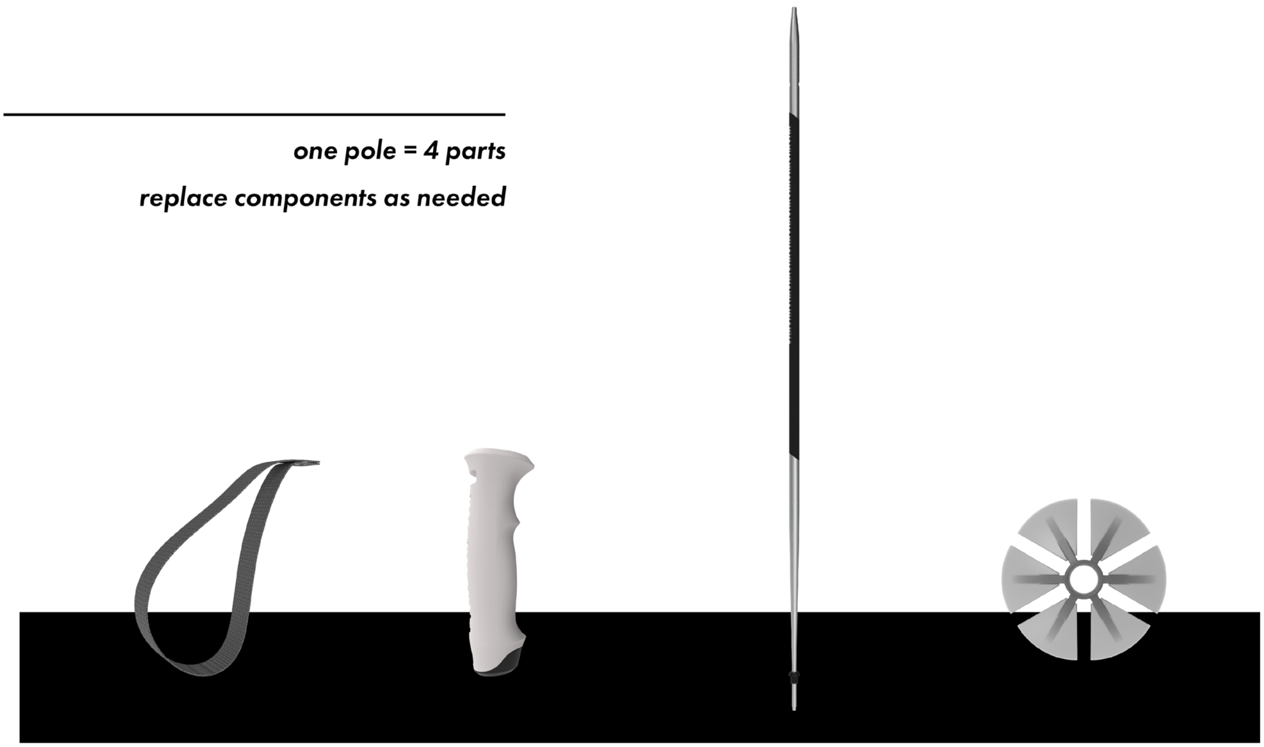

Figure 28. Pole Components

Figure 29. Pole Customization Examples

Figure 30. In Context

Figure 31. In Context

6 Results and Discussion

6.1 APPLYING THE METHODOLOGY

Now that there is a completed design, it can be compared to other existing systems following the CE Methodology developed in Section 3. Three other existing ski pole systems were chosen to compare against. One is a standard set of aluminum ski poles, and two consider themselves to be “sustainable poles”: one bamboo set (Soul Poles) and one flax fiber composite set (Kang). These poles were chosen to reflect the variety of poles available on the market. It should be noted that none of these were specifically designed for the circular economy, so they will be lacking in a lot of areas. This methodology, however, should highlight where they can make improvements if desired. Figures 25 - 28 show the different systems that will be compared.

Table 8 displays some of necessary information for the systems - the disassembly score and material of each component for each system. This information will be utilized in the score sheets.

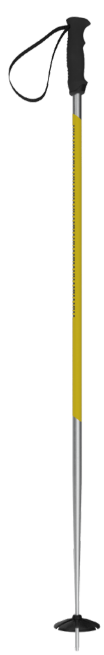

Figure 25. VITA

Figure 26. Kang

Figure 27. Soul Poles

Figure 28. Black Crows

Table 8. Materials and Disassembly								
	VITA		***Kang***		***Soul Poles***		***Black Crows***	
	material	**disassembly**	**material**	**disassembly**	**material**	**disassembly**	**material**	**disassembly**
strap	hemp webbing	3	nylon webbing	3	recycled PET	3	nylon webbing	3
grip	natural rubber	3	PP	1	recycled PET	1	PP	1
shaft	recycled aluminum	3	flax composite	1	bamboo stalk	1	5083 aluminum	1
basket	TPU	4	TPU	3	TPU	3	TPU	1

The completed score sheets for each system are shown in Appendix B. As discussed in Section 3, the sustainability scores were obtained from the Sustainable Minds software using the materials and manufacturing processes. Kang utilized a flax composite for their shaft. This material has gained a lot of recent traction for the sustainable benefits and physical properties it provides. It has been used in the automotive and sports industries. This form of natural fiber reinforcement has a low density and properties similar to carbon fiber. It is an interesting choice for replacing the tradition carbon fiber composite shafts, however, it lacks in terms of its recyclability. Soul Poles, and several other "sustainable" ski pole companies, have turned back to traditional ski poles and opted for the bamboo shaft. This shaft is made up of a stalk of bamboo, cut when the diameter reaches the correct point. It is then dried and treated. These shafts were used for thousands of years and are incredibly strong and light. Bamboo poles have become a controversial product in the skiing industry: some love and some hate the bamboo shaft. They are prone to splintering when they break. They are also significantly more expensive than a standard aluminum shaft, and many will not pay the premium.

Table 9. Final Rating Matrix [F]				
	VITA	Kang	Soul Poles	Black Crows
repairability	0.677	0.085	0.185	0.054
recyclability	0.630	0.140	0.140	0.080
reusability	0.380	0.090	0.380	0.140
sustainability	0.269	0.269	0.414	0.047

This information was all gathered from available sources, modeling on the computer, and making assumptions. Not all of the materials for each of the companies were given, so if that information is later found, the assumptions can and should be changed.

Table 9 shows the completed final rating matrix using the scores from each of the factors. This matrix was transposed and multiplied by the criteria weights {W}, and the results are shown in descending order in Table 10.

Table 10. Final Ratings	
VITA	0.583
Soul Poles	0.225
Kang	0.116
Black Crows	0.077

6.2 DISCUSSION

This methodology was created specifically for the case study of ski poles in a circular economy. The sub-criteria on the score sheets relate directly to the design of ski poles (for example, the disassembly score breaks the factor down into scores of the grip, strap, shaft, and basket). It can, however, be easily modified for a different system. The process remains the same, and the scoring of the system is still valid. If using for another product, it must be listed in its component parts so that the disassembly, recyclability of the materials, etc... may be scored. It is important to remember that if the components of the system are changed, the scores must be normalized into a vector with a maximum of 10.

As noted in section 5.1, this methodology was created to rank products in their fitness for the circular economy. The three competing systems, however, were not designed for the circular economy so therefore it is not surprising that VITA scored significantly higher than the rest. Soul Poles scored the second highest, followed by Kang, and Black Crows scored the lowest. Even though Soul Poles and Kang were designed to be sustainable (Soul Poles sustainability of materials score was higher than VITA), when it comes to the circular economy, they fall far behind. This highlights the importance of the other factors that are often ignored. Black Crows, although good ski poles, had no consideration of sustainability or the circular economy, and the results reflect this.

This methodology is very good at highlighting where the system fails to fit in the circular economy. For example, in repairability, one of the sub-criteria is whether or not new parts are offered. It is a simple, binary, yes or no question for each of the components. It is clear, then, that if these parts are not offered, the repairability score will decrease. By having the user of this methodology input quantitative numbers into the system, it is easier to understand how their design will work within the circular economy.

6.3 LIMITATIONS OF STUDY

As mentioned above, not all of the materials of the competing systems can be confirmed. Assumptions were made, but these values would be even more valid if this information were available. Similarly, the sustainability software available does not have the data for every material used. The bamboo poles, for example use a single bamboo stalk to create the shaft. There was no data available for what the carbon impact of this (including growth, transport, etc...). Additionally, TPU (thermoplastic polyurethane) was lacking from the database. Every basket likely used this material, so it is hard to score them without this information. Once this data becomes available, the sustainability calculations can be redone for more accurate results.

Right now, the scores between VITA and the next highest scoring competitor, Soul Poles, is quite dramatic. If the other poles had been designed with the circular economy in mind, the results would surely differ. In the future, as the circular economy gains more momentum, hopefully more poles will be designed for the CE and this methodology can be reapplied and potentially more factors could be added.

7 Validation

It is assuring to see that the system works well within the circular economy, however, it won't succeed if the customers do not buy into the system. The design and company system design must be validated by the users in order to know if it will be successful or not. The validation of this system was done in two ways: user testing to get real time feedback on the design and a second user survey to gauge interest in this system.

7.1 User Testing

The initial prototypes and concepts were tested on several users at a ski resort in Utah. The goals for this system were to see which styles they preferred skiing with the most, how easy it was for someone not involved in this thesis to put the modular system together, and understand what kind of experience they have had with their ski poles in the past.

Three grip styles and three basket styles were tested. The baskets consisted of a powder basket, a standard basket, and a small powder basket. They are shown in Figure 29. Below are the open ended questions that were asked to each participant.

	method	questions
attachment	each user receives unassembled parts to attach grip and strap general diagram is presented user puts the grip together ranks ease and gives commentary	How easy was attaching each grip? Which did you prefer? Why? How sturdy does it feel? Would you be willing to repeat this to change out your grips as desired?
grips	already put together poles are given to the user and ski on each grip give commentary and feedback on which they prefer and why	Which grip was your favorite? Why? Do you prefer a slim grip or ergonomic? Do you prefer texture or no texture? Do you prefer a finger registration or no? What did you like and dislike about each option?
baskets	already put together poles are given to the user and ski with each basket (ideally in different snow conditions) compare standard basket, small powder, and regular powder basket give commentary and feedback on which they prefer and why	Which basket was your favorite? Why? Did you prefer the standard basket or the small powder basket? Do you prefer standard or powder? Why? What did you like or dislike about each option?

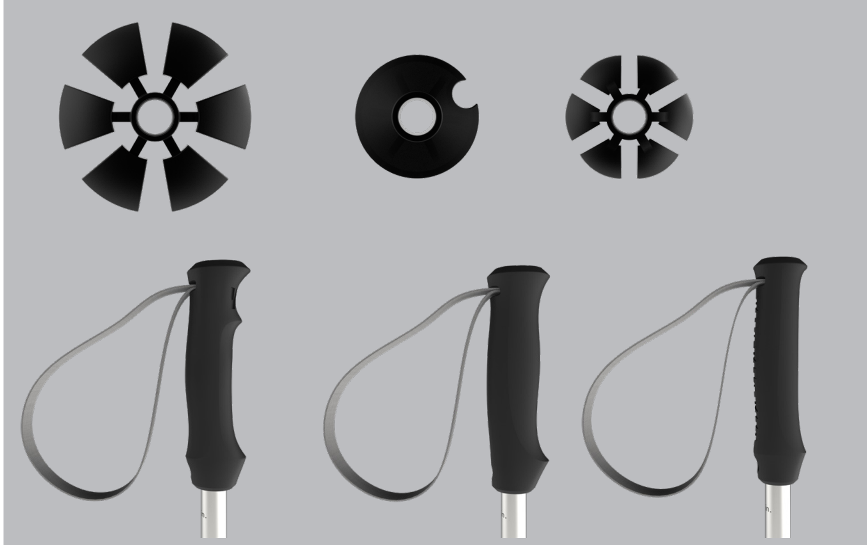

Figure 29. Models Tested

Every user preferred the powder basket due to aesthetics. A smaller powder basket was included to see if they liked the aesthetics of the powder basket but the size of the standard basket. The small powder was the unanimous least favorite. It was also noted that the color of the baskets used (blue, Figure 30 was exciting because most baskets on the mountain are currently black.

The majority of participants preferred the grip style that had the finger registration marks. There were, at this point, still necessary adjustments to be made in the model in order to increase the ergonomics, but many still preferred it over the slimmer styles. The user with the smallest hands, however, preferred the slim grip and remarked that the larger grip "made their hands tired". Another consideration about the grips is many park skiers prefer a slim grip for their ski style (less bulky in their hand as they are doing ski grabs in air), but none of the participants in this study were free skiers.

The grip attachment method was previously discussed in section 4 (shown in Figures 4 and 5), but the users were also asked to assemble the systems. Similar to what I had found, the second system was more difficult for the users to put together. The basket attachment system was also explored in section 4, but the users were only asked to put on the basket utilizing the friction fit basket using a pole with a basket attachment already in place. Figure 31 shows a detaching and reattaching the basket. No user had any problem with this system.

The participants reported that the system felt sturdy and the poles felt good to ski with. The concern with the grip attachment weakening the system proved to not be a concern

Figure 30. Blue Powder Basket

Figure 31. Basket Attachment

Figure 32. Grips Tested

as the grip stayed tight and had no wiggle. The poles were used in all types of conditions: double black diamond mogul runs, using the poles to push on cat tracks, and leaning on them in lift lines.

7.2 User Survey II

A second user study was conducted to further validate the system. This survey was distributed through Reddit and Newschoolers (a skiing specific forum). 261 responses were received. It should be noted that 82% of the responses were male.

The first part of the survey asked the users to build their desired poles. The options included two grip styles, two basket styles, and 10 color options of each. The purpose of this experiment was to see what kind of colors or customization users really wanted. Black and grey were the most popular color choices in every category, but only 14% of respondents wanted *only* grey or black options. The rest of the colors were split up randomly. Ultimately, the colors chosen to include in the product were black, grey, blue, yellow, and pink. All of

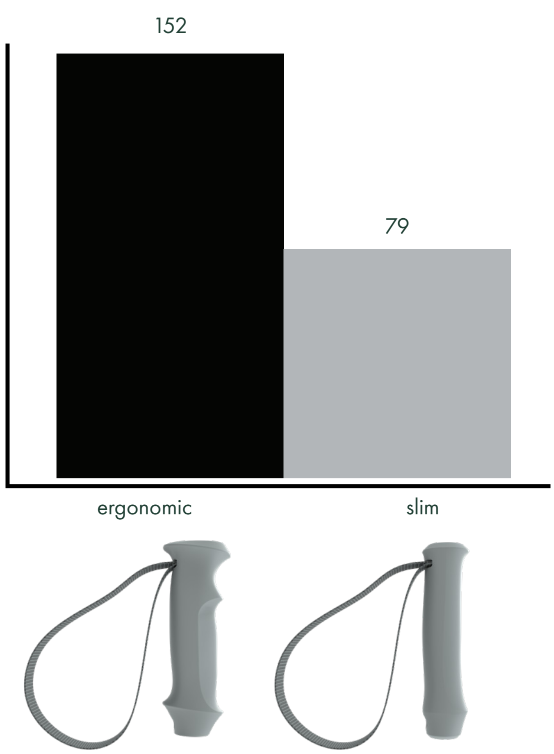

Figure 33. Preferred Grip Style

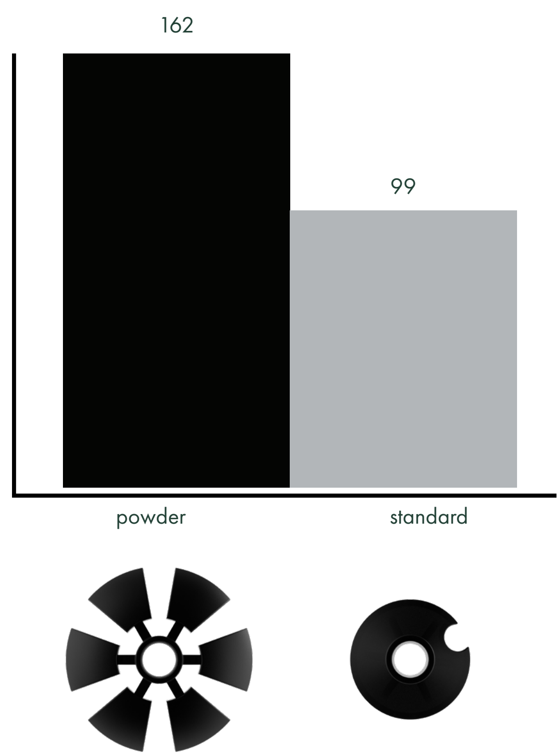

Figure 34. Preferred Basket Style

these colors were popular for the different components and also are colors that can be mixed up easily to create a lot of different custom styles.

The preferred styles of the grip and basket are shown in Figure 33 and 34. Though not evident in the user testing, there are significant numbers for both styles shown in the user survey.

In this survey, 78% of respondents had broken or damaged a ski pole. As with the first user survey, the majority of reported damage occurred in the shaft. 44% of respondents threw the good pole away, and 16% kept the pole to use mismatched.

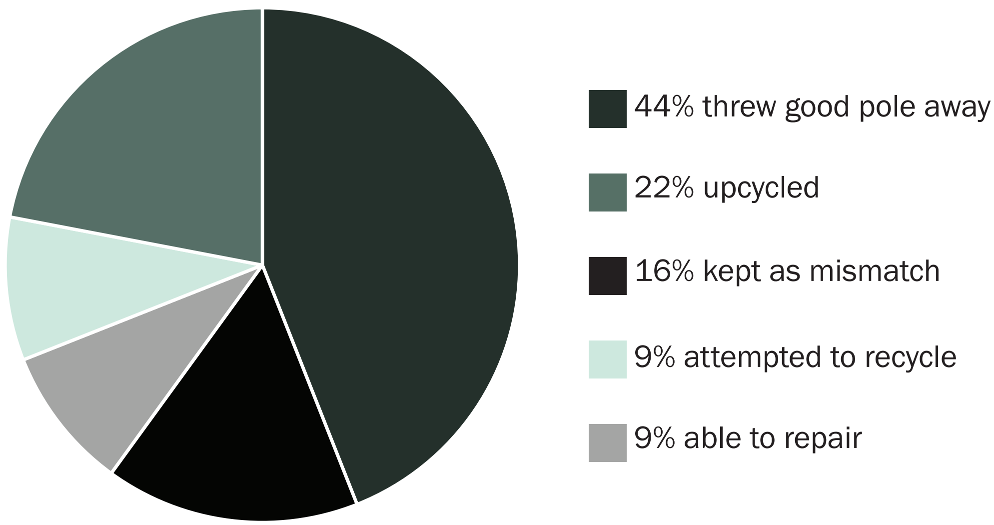

Figure 35. Responses to what users did with unbroken pole

89% of respondents had not attempted to recycle their old set of poles. A few people left comments on this section describing the difficulty they had in recycling. Some recycling centers would not take them and they had to drive farther away. Other centers would take them but required them to be fully disassembled. 73% of respondents said they would be more likely to recycle their poles if they were easy to disassemble and 92% said they would be more likely to recycle if there were a convenient location to do so (e.g. company collection or at the mountain itself). Though people saying they would be more likely to do something versus them actually doing something may not always align, these numbers show an extremely high percentage of people who like to recycle their poles. Right now it is so inconvenient to do so, and nearly 90% haven't attempted. Making the poles more recyclable and even getting a fraction of people to try would be a success.

When asking respondents if the broken part of the pole were easily replaceable, would they rather replace damaged piece or buy new poles, 72% said they would rather replace the damage. This number shows a significant amount of people who would be interested in the modular concept. Of the respondents that said they would rather buy a new pair, 30% said it was because they were looking for a new style. The modular concept could also account for these people, making an upgrade or style change simple.

This second user survey provided a lot of optimistic feedback about modular poles for the circular economy. Not only would it benefit the environment, but customers can see the value of it for themselves.

Below are some of the comments and feedback that people left:

“Dope stuff! Love the idea for recycling poles!”

“Love this idea, I have broken my pole baskets a few times and as my poles are like 20 years old I can’t ever find replacements that actually fit”

“If you made custom poles like that it would be so sick, I would definitely cop”

“I work in a rental ski shop where poles are just tossed aside when there is a crack in the shaft or a strap or basket is missing. If these parts were more readily available it’d make repairs possible instead of tossing an entire pair into the dump”

“I keep a parts bin and reuse various parts when I can”

8 Conclusion and Future Work

This paper presented a methodology for ranking products or concepts in their fitness for the circular economy. The results are quantified through a multi-criteria decision making analytical hierarchy process. By empirically scoring the concepts in repairability, reusability, recyclability, and sustainability, a final ranking can show which product was more successful in their design for the circular economy. This was done through a case study of ski poles. The concept is dependent on the modularity of the poles and on the company's system design for providing ease of repairs and end of life management.

The methodology successfully created a ranking of the case study company, VITA, and three other competing systems. The results demonstrated that by designing with these specific factors in mind, a product can be much better suited and tailored for the CE. The modular ski poles were able to eliminate all of the epoxy and components that were not dismantle-able from the pole, ensuring ease of repair, upgrades, and recycling. Further testing on the methodology should be performed on products designed specifically for the circular economy ranked against each other.

This system was validated through a user study that showed the optimism for the success of such a product and customer adoption. Feedback was received about the users' excitement for the customization option and their reported likelihood to recycle a more disassemble-able product.

This modular system also opens up the possibility for future advancements of the poles. New color swatches and styles could be created and easily modified to the customer's current poles. Because ski poles are typically only used in the winter months, there is potential for these winter ski poles to transition to a summer hiking sticks with just a few adjustments. Ski rental shops could also realize a huge benefit from system in the future. If they were able to just replace a specific component, the shop could save money purchasing just that part rather than new poles.

Next steps for the VITA include a pretotyping test. Pretotyping, as opposed to prototyping, is testing the market acceptance for an idea. This is done through "skin-in-the-game" tests that get information from users (emails, phone numbers, money for first releases, etc...) which provide valuable insight that consumers will *actually* buy into the system. Though people have claimed that they would be interested in the modular ski pole system, garnering actual interest will ensure that this product will succeed and survive in the market. Promoting the idea at ski resorts and in Instagram ads could result in interested parties email addresses who could be a part of the initial product launch. The modularity of this product means that it can accept live customer feedback, make new iterations of a specific component, and update those parts.

Further next steps for this pole include testing of the strength of the shaft itself. The design relies upon a series of holes in the aluminum shaft, which, undoubtedly weaken that area. However, these areas are not where the shaft tends to fail. Failure in the aluminum tubing typically occurs in the middle of the shaft where the torque on the system will be higher (versus where a couple of inches off the ends where the holes currently exist). Additionally, these ends are both reinforced with the grip and the basket pieces, meaning they would have to fail before the aluminum would fail. Testing is needed to see what the failure rate is of this shaft system is and how that will affect the poles capabilities.

This system may be used both as a way to compare competing products and as a tool to aid the designer in their development of a more sustainable product. The designer may use this methodology to compare several concepts they have and further develop the one with the highest CE score. Further, they system may highlight areas in which their concept falls short of a perfect circular economy score on the score sheets and they may make modifications.

Designing for the circular economy is something that all designers should be prepared to do. Transitioning to a more sustainable future is only possible if products are treated in a circular fashion rather than the take-make-waste linear mindset. Doing so not only reduces waste, but also provides considerable value to the customer. In this paper, it has been proven that modular design creates a product more fit for the circular economy while also providing benefits to customers.

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APPENDIX A

User Survey I

What type of ski poles have you bought before?

- Aluminum
- Carbon Fiber
- Bamboo
- Other

Specify other...

Favorite you have purchased?

- Aluminum
- Carbon Fiber
- Bamboo
- Other

Specify other...

Where have you purchased poles from before?

- Directly from manufacturer
- Online Retailer
- In person / ski shop
- Other

Specify other...

Rate the following in importance when buying ski poles:

Cost

1: not at all important
5: most important

1 2 3 4 5

Weight

1: not at all important
5: most important

1 2 3 4 5

Durability

1: not at all important
5: most important

1 2 3 4 5

Sustainability

1: not at all important
5: most important

1 2 3 4 5

Appearance

1: not at all important
5: most important

1 2 3 4 5

Other factors you consider important

e.g. telescopic shaft, grip shape, etc...

Have you ever broken or damaged a ski pole?

YES | NO

Which component was damaged?

- Shaft ☐
- Grip ☐
- Strap ☐
- Basket ☐
- Tip ☐
- Other ☐

If damage was only to one pole, what did you do with the remaining pole?

- Threw out ☐
- Recycled ☐
- Upcycled ☐
- Other ☐

Did you attempt to repair or fix it?

YES | NO

Were you successful with the repair?

YES | NO

Have you ever attempted to upgrade or replace a specific component of your poles?

YES | NO

Which component?

- Shaft

- Grip

- Strap

- Basket

- Tip

- Other

Have you ever attempted to recycle/upcycle your old poles?

YES | NO

If you have owned more than one pair of poles, what was the reason for purchasing a new pair?

- Damaged
- Old
- Outgrew
- Aesthetics
- Lost/Stolen
- Other

How much are you willing to pay for ski poles?

Write a few keywords for preferred ski pole aesthetics

Designs, colors, etc...

Preferred color or accent color of poles?

Pick a color

APPENDIX B

Scores of factors

Repairability

repairability index for vita			
criteria	**sub-criteria**	**score**	**weighted score**
documentation	does a repair guide exist?	1 /1	10 /10
disassembly	how easy it the system to disassembly?		
	strap	3 /4	
	grip	3 /4	
	shaft	3 /4	
	basket	4 /4	
		13 /16	16.25 /20
part availability	are new parts offered?		
	strap	1 /1	
	grip	1 /1	
	shaft	1 /1	
	basket	1 /1	
		4 /4	50 /50
company repairs	does the company offer a warranty or repairs?	1 /1	20 /20
			96.25 /100
			9.625 /10

repairability index for kang			
criteria	**sub-criteria**	**score**	**weighted score**
documentation	does a repair guide exist?	0 /1	0 /10
disassembly	how easy it the system to disassembly?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	3 /4	
		8 /16	10 /20
part availability	are new parts offered?		
	strap	0 /1	
	grip	0 /1	
	shaft	0 /1	
	basket	1 /1	
		1 /4	12.5 /50
company repairs	does the company offer a warranty or repairs?	0 /1	0 /20
			22.5 /100
			2.25 /10

repairability index for Soul Poles			
criteria	**sub-criteria**	**score**	**weighted score**
documentation	does a repair guide exist?	0 /1	0 /10
disassembly	how easy it the system to disassembly?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	3 /4	
		8 /16	10 /20
part availability	are new parts offered?		
	strap	0 /1	
	grip	0 /1	
	shaft	0 /1	
	basket	1 /1	
		1 /4	12.5 /50
company repairs	does the company offer a warranty or repairs?	1 /1	20 /20
			42.5 /100
			4.25 /10

repairability index for Black Crows			
criteria	**sub-criteria**	**score**	**weighted score**
documentation	does a repair guide exist?	0 /1	0 /10
disassembly	how easy it the system to disassembly?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	1 /4	
		6 /16	7.5 /20
part availability	are new parts offered?		
	strap	0 /1	
	grip	0 /1	
	shaft	0 /1	
	basket	0 /1	
		0 /4	0 /50
company repairs	does the company offer a warranty or repairs?	0 /1	0 /20
			7.5 /100
			0.75 /10

Repairability Alternative Priorities	
VITA	0.68
Kang	0.08
Soul Poles	0.19
Black Crows	0.05

Reusability

reusability index for VITA			
criteria	sub-criteria	score	weighted score
reuse	can the poles be reused, resold, or donated	1 /1	30 /30
collection	are the old poles and parts collected by company	1 /1	20 /20
refurbish/remanufacture	can broken/old parts be updated?		
	strap	3 /4	
	grip	3 /4	
	shaft	3 /4	
	basket	4 /4	
		13 /16	24.375 /30
resell	are old or refurbished poles resold by the company?	2 /2	20 /20
			94.38 /100
			9.44 /10

reusability index for kang			
criteria	sub-criteria	score	weighted score
reuse	can the poles be reused, resold, or donated	1 /1	30 /30
collection	are the old poles and parts collected by company	0 /1	0 /20
refurbish/remanufacture	can broken/old parts be updated?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	3 /4	
		8 /16	15 /30
resell	are old or refurbished poles resold by the company?	0 /2	0 /20
			45 /100
			4.5 /10

reusability index for Soul Poles			
criteria	sub-criteria	score	weighted score
reuse	can the poles be reused, resold, or donated	1 /1	30 /30
collection	are the old poles and parts collected by company	0 /1	0 /20
refurbish/remanufacture	can broken/old parts be updated?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	3 /4	
		8 /16	15 /30
resell	are old or refurbished poles resold by the company?	1 /2	10 /20
			55 /100
			5.5 /10

reusability index for Black Crows			
criteria	sub-criteria	score	weighted score
reuse	can the poles be reused, resold, or donated	1 /1	30 /30
collection	are the old poles and parts collected by company	0 /1	0 /20
refurbish/remanufacture	can broken/old parts be updated?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	1 /4	
		6 /16	11.25 /30
resell	are old or refurbished poles resold by the company?	0 /2	0 /20
			41.25 /100
			4.125 /10

Reusability Alternative Priorities	
VITA	0.63
Kang	0.14
Soul Poles	0.14
Black Crows	0.08

Recyclability

recyclability index for VITA			
criteria	**sub-criteria**	**score**	**weighted score**
disassembly	can each piece be isolated?		
	strap	3 /4	
	grip	3 /4	
	shaft	3 /4	
	basket	4 /4	
		13 /16	24.4 /30
recyclability	is each component recyclable?		
	strap - hemp webbing	1 /2	
	grip - natural rubber	2 /2	
	shaft - 6061 aluminum	2 /2	
	basket - TPU	2 /2	
		7 /8	61.25 /70
			85.6 /100
			8.6 /10

recyclability index for kang			
criteria	**sub-criteria**	**score**	**weighted score**
disassembly	can each piece be isolated?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	3 /4	
		8 /16	15 /30
recyclability	is each component recyclable?		
	strap - nylon webbing	1 /2	
	grip - PP	2 /2	
	shaft - flax composite	0 /2	
	basket - TPU	2 /2	
		5 /8	43.8 /70
			58.8 /100
			5.9 /10

recyclability index for Soul Poles			
criteria	**sub-criteria**	**score**	**weighted score**
disassembly	can each piece be isolated?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	3 /4	
		8 /16	15 /30
recyclability	is each component recyclable?		
	strap - recycled PET	2 /2	
	grip - recycled PET	2 /2	
	shaft - bamboo	2 /2	
	basket - TPU	2 /2	
		8 /8	70 /70
			85 /100
			8.5 /10

recyclability index for Black Crows			
criteria	**sub-criteria**	**score**	**weighted score**
disassembly	can each piece be isolated?		
	strap	3 /4	
	grip	1 /4	
	shaft	1 /4	
	basket	1 /4	
		6 /16	11.3 /30
recyclability	is each component recyclable?		
	strap - nylon webbing	1 /2	
	grip - PP	2 /2	
	shaft - 5083 aluminum	2 /2	
	basket - TPU	2 /2	
		7 /8	61.3 /70
			72.5 /100
			7.3 /10

Recyclability Alternative Priorities	
VITA	0.38
Kang	0.09
Soul Poles	0.38
Black Crows	0.14

Sustainability of Materials Values and Scores		
	CO_2 kg. eq	Normalized Scale
VITA	0.718	7.4
Kang	0.664	7.6
Soul Poles	0.341	8.8
Black Crows	2.78	0.0

Sustainability Alternative Priorities	
VITA	0.27
Kang	0.27
Soul Poles	0.41
Black Crows	0.05

APPENDIX C

User Survey II

Ski Pole Questionnaire

A study into how recreational alpine skiers purchase, use, and dispose of ski poles

Demographics

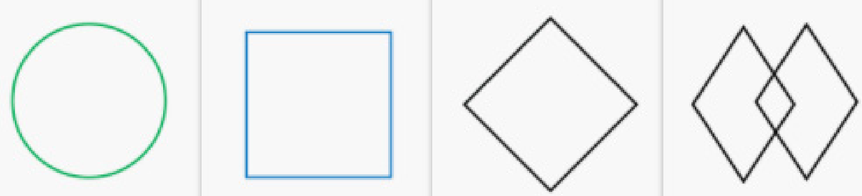
Age

Gender

- Male ○
- Female ○
- Other ○

Ski level

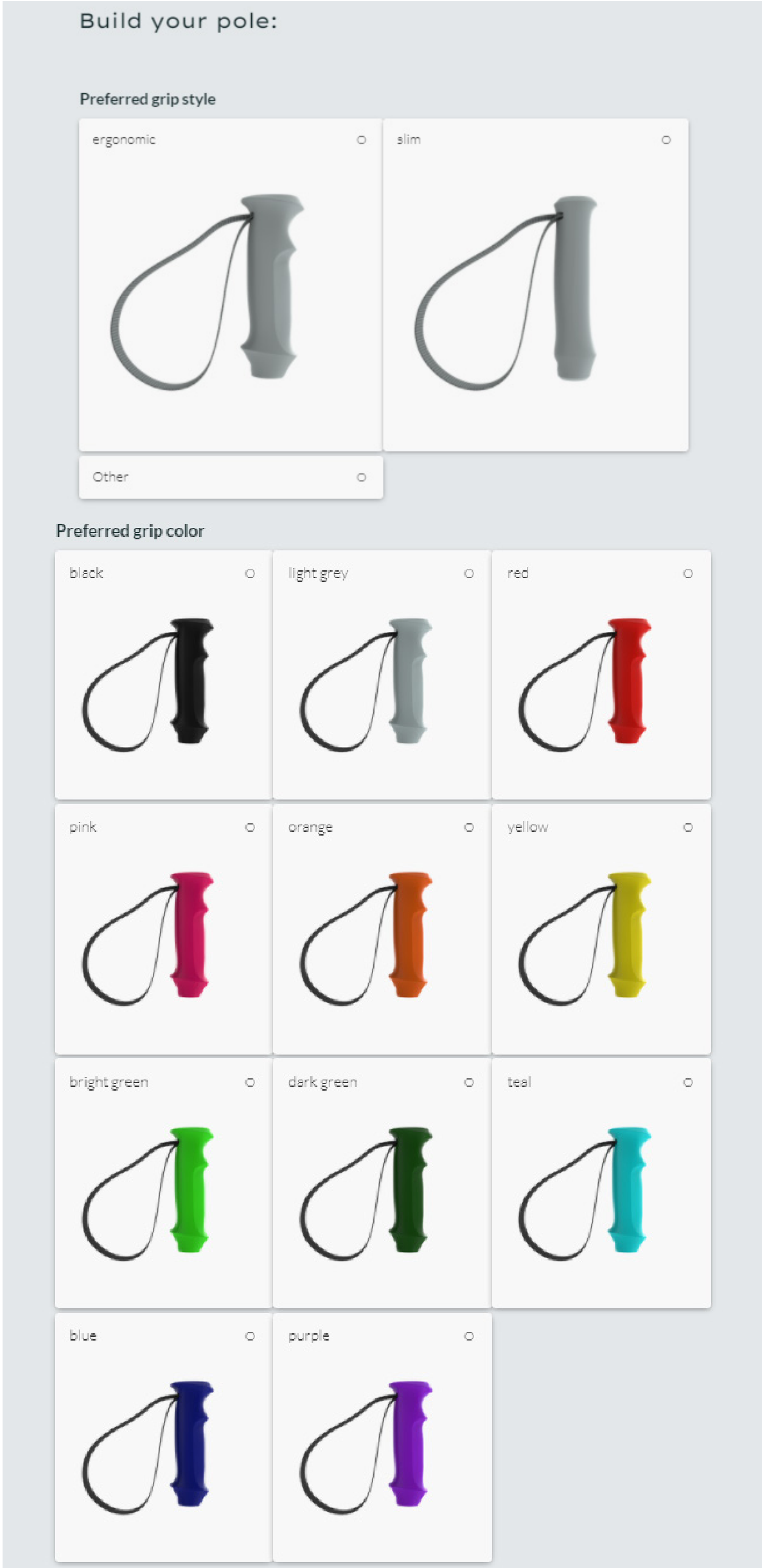
Beginner ○ | Intermediate ○ | Advanced ○ | Expert ○



Approximate ski days per year

What type of ski poles have you bought before?

- Aluminum □
- Carbon Fiber □
- Bamboo □
- Other □


Build your pole:

Preferred grip style

ergonomic

slim

Other

Preferred grip color

black

light grey

red

pink

orange

yellow

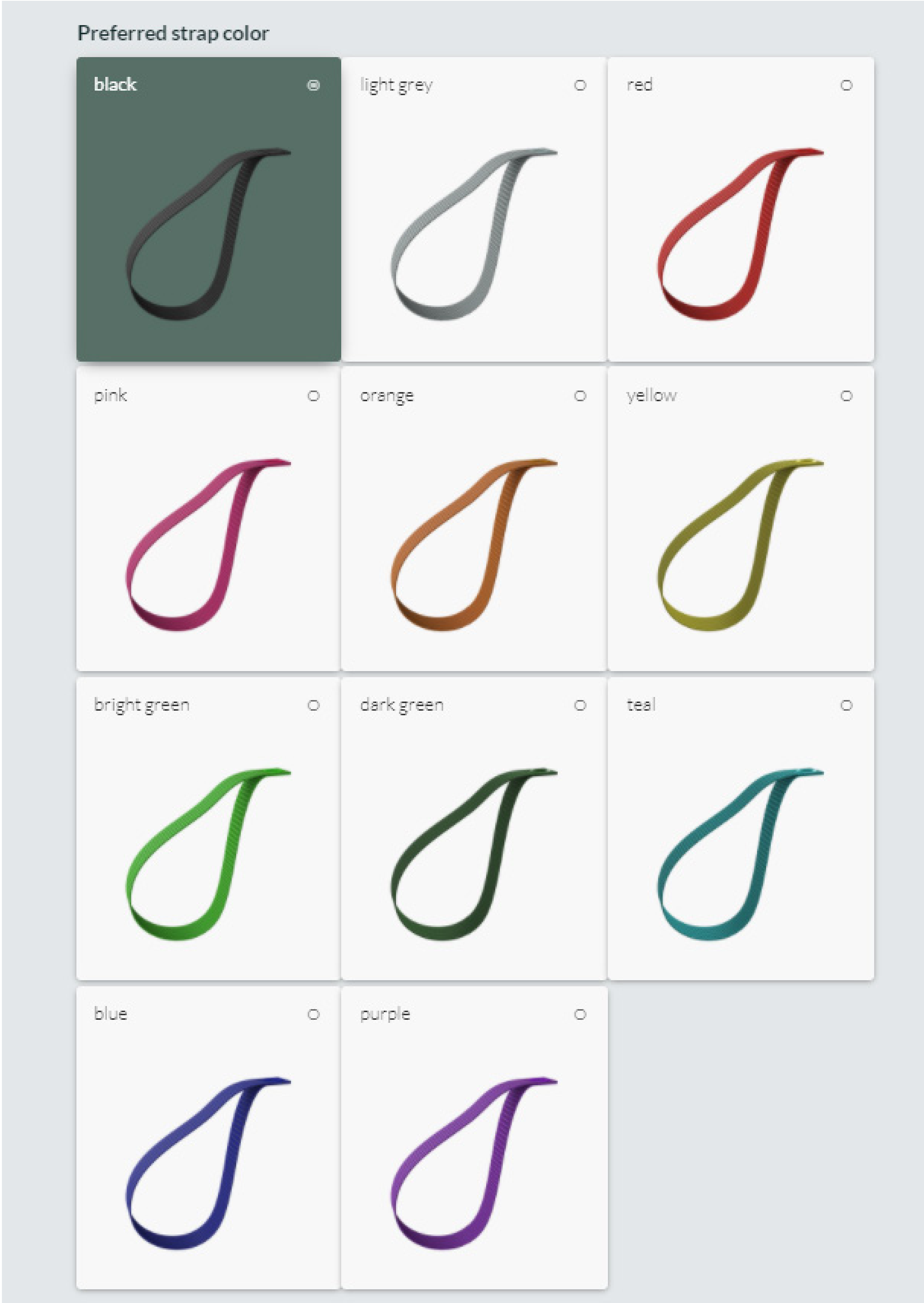
bright green

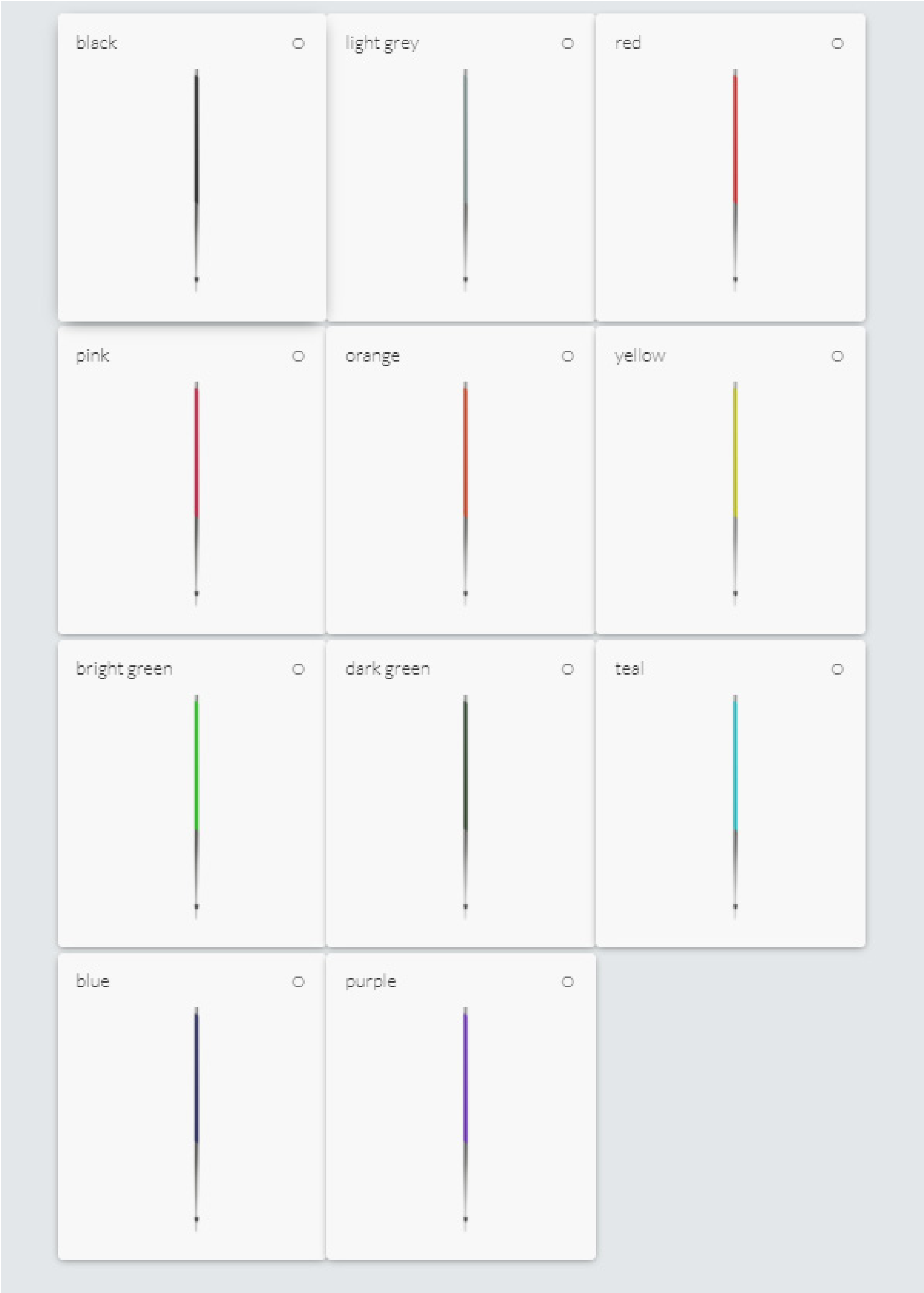
dark green

teal

blue

purple

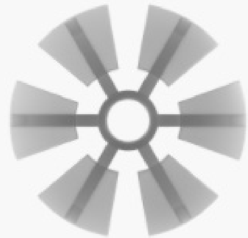

Preferred strap color
black
light grey
red
pink
orange
yellow
bright green
dark green
teal
blue
purple


black
light grey
red
pink
orange
yellow
bright green
dark green
teal
blue
purple

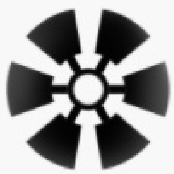
Preferred basket style

standard

powder

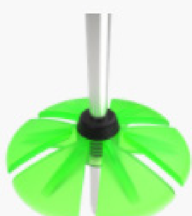


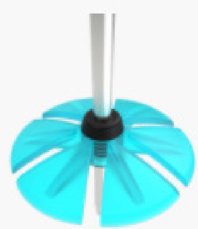
Preferred basket color











Have you ever broken or damaged a ski pole?

YES | NO

Which component was damaged?

- Shaft ☐

- Grip ☐

- Strap ☐

- Basket ☐

- Tip ☐

- Other ☐

If a broken part of the pole were easily replaceable, would you prefer to:

- Buy new poles ☐
- Replace damaged part of pole (i.e., replace shaft) ☐
- Other ☐

If damage was only to one pole, what did you do with the remaining unbroken pole?

- Threw out ☐
- Recycled ☐
- Upcycled ☐
- Other ☐

Have you ever recycled your poles?

YES | NO

Did you find it difficult to do/an inconvinence? Why/why not.

Would you be more likely to recycle your poles if they were disassemblable?

- Yes
- No
- Other

Would you be more likely to recycle your poles if there were a convenient location to do so? (i.e., in the mountain village, company collection, etc..)

- Yes
- No
- Other