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HONORS THESIS

Quantifying Eco-Friendliness of Plastic, Paper, and Reusable Bags

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ABSTRACT

The plight of the consumer in regards to making eco-conscious decisions is growing as concerns regarding the environment increase. This study was conducted in an effort to give consumers a tool to combat some of this issue and compare the types of shopping bags they use in terms of eco-friendliness. Research conducted in this avenue thus far contains convoluted conclusions, all made with consideration of some variables, but not all. This purpose of this study therefore lay in trying to give consumers a standardized tool to compare bag types that considered variables across all stages of a bags' life (pre-use, in-use, post-use). We determined which variables were of importance and how they were related to each other using Interpretive Structural Modeling. We then took these variables and, through Analytical Hierarchy Processes, found the respective weights each variable would need to be considered in a model. Using survey results, mathematical processes, and reviewed literature, we were able to construct a model that functions like an index. The outputted index score allows for consumers to make comparisons about a bags eco-friendliness across bag types. The constructed index score is applicable to the decision making of an individual consumer, but requires future research before it can be used to draw overarching conclusions.

INTRODUCTION

As the debate concerning climate change rages in the forefront of today's society, numerous factoids and statistics related to the topic are seemingly generated out of thin air. Of particular relevance is the debate revolving around the use of reusable bags or the traditional paper or plastic alternatives. As eco-responsible beings, we must sort through what has been accepted to be true versus what is true in regard to the type of bag we choose to use. As an emerging adult, I was arriving to the time when I had to make the decision for myself. I had always considered plastic bags to be far worse for the environment than paper or reusable alternatives so I was surprised when I found heavy research backing the use of plastic bags. "Each region serves its own custom blend of alarmist rhetoric; coastal areas blame the wispy totes for everything from asphyxiated sea turtles to melting glaciers, while inland banners decry the bags' role in urban landscape pollution and thoughtless consumerism. But a closer look at the facts and figures reveals shaky science and the uncritical repetition of improbable statistics tossed about to shore up the case for a mostly aesthetic, symbolic act of conservation," (Mangu-Ward 2015). Given numerous arguments advocating for the use of plastic bags, differing from what I had assumed to be true and current public sentiment, I began to develop the idea for this project.

Each researched work made claims on either side of the argument, but the severity and reasoning differed. Conclusions were dependent on the variables used to determine environmental impact, which can range from production of the bag to post use (Evans 2019). For instance, one study found that a shopper "would have to reuse an organic cotton bag 2,000 times before it equaled the environmental impact of *one* disposable bag" because "manufacturing (for cotton bags) requires far more water than plastic bags," meaning it is less wasteful to produce a plastic bag ("Kroger's Feel-Good Ban On Plastic Bags Is Worse Than Pointless" 2018). This looks at the perspective of the manufacturing process. Another study looked at the variable of inputs to make the bags in addition to the manufacturing process. The typical plastic bag found in retail stores is made from non-renewable resources while paper bags are made from pulp in trees, which is a renewable source. Yet, the process the pulp must undergo to be used as a paper bag consumes "tremendous amount(s) of energy from fossil fuels, electricity, various chemicals, etc.," (Muthu, Subramanian, Senthilkannan 2012). This is aside from needing to tap into the tree and possibly impact the animals that rely on it. Seeing all the differences in claims made me realize that being environmentally friendly is a multifaceted concept and can be hard to define. What does it mean to be ‘eco-friendly’? Which variables should be considered when determining which type of bag is better for the environment? Do some variables impact the eco-friendliness of a bag more than others (for instance, is the manufacturing process more taxing than the disposal process)?

Given my mathematics background, I began to question if there was a way to bring these variables together to offer a standardized approach to such grey questions. Is it possible to build a model that quantifies eco-friendliness? Is there a way to use mathematics to determine which bag is best for the environment? The scope of this project involves defining what each bag is and what it means to be environmentally friendly, identifying key areas of potential variables over the lifecycle of a bag, and quantifying those variables to work together in a model. Through this, I hope to be able to answer the following questions.

- How does this study define plastic, paper, and reusable bags?
- Which variables should be used to determine which type of bag is better for the environment?
- Do some variables impact a bag’s eco-friendliness more than others?
- Is there a model that can be constructed to weight these variables accordingly to assess which type of bag is best for the environment?

With a successful model, the question of which type of bag is best for the environment should be answered while considering all avenues. Where some bags may out perform others in certain areas, I found that research lacked answering the question of which was better overall. Thus evolved the idea and purpose of my project.

LITERATURE REVIEW

As mentioned above, there has been a lot of work done in this area over which type of bag is the best for the environment. While paper bags are not as heavily discussed in the literature reviewed, there is a lot to be found on the use of plastic and reusable alternatives. That said, before delving into the thick of the review, it is important to understand the different types of bags that this study will examine: plastic, paper, and reusable.

The plastic bags consumers in America are most used to seeing are High Density Polyethylene bags, or HDPE (Hermes 2019). The process used to create these bags is called film extrusion in which polyethylene beads are loaded into a barrel which uses heat, pressure, and friction to melt the beads into a form they can be manipulated in (Canadian Plastic Bag Association 2019).

Paper bags are made from paper pulp and the ends are folded and glued together through a heating and pressing process ("Brown Paper Bags Guide" 2019). The most commonly used paper for these types of bags is Kraft which "is manufactured from wood chips," (Emily 2018). When the woodchips are heated, they break down into pulp and byproducts that must then be "screened, washed, and bleached," before it can take the form of the paper bag (Emily 2018). It is important to note that some paper bags are made from recycled cardboard. This study will ignore recycled paper bags and consider only the bags made from raw material such as wood chips.

Lastly, reusable bags will be examined which, for the sake of this study, are limited to cloth bags. Cloth bags are made from cotton which can be grown traditionally or organically. Traditional cotton bags are made from "a renewable crop source but require chemicals and pesticides and consume large quantities of water," (Canadian Plastic Bag Association 2019). Organic cotton bags are made from cotton that grows without the use of pesticides, but still requires a lot of water. Though cloth bags are made from a renewable resource, the traditional manufacturing accounts for "16% of the world's pesticide use and requires high water consumption" for both the crop and the production thereafter (Canadian Plastic Bag Association 2019). This study will be considering both traditionally and organically manufactured cloth bags.

Each of these bags will be looked at in terms of their eco-friendliness. Eco-friendly, as defined by the Oxford Dictionary, means 'not harmful to the environment.' In a literal sense, none of the bags are eco-friendly as each harms the environment in some form. Thus, this study seeks understanding which type of bag causes reduced or minimal harm to the environment.

Of the types of bags examined, there is some debate over which type of bag is the most eco-friendly. There is reason for the differing conclusions in the field; conclusions are impacted by both the variables considered and the timeline they are observed on. With slight modifications in each of these areas, there are infinite variations studies can take which leaves room for these differing conclusions. To help combat such variations, more standardized approaches have emerged in the field. One of the most standardized methods of assessing environmental impacts is through Life Cycle Assessments, or LCAs. In fact, at one time LCAs were the "only internationally standardized method of ecological product assessment," (Klopffer & Grahl 2014). LCA studies "deal with the quantification of the environmental impact made by any product/process in its useful time," (Klopffer & Grahl 2014) and have "developed rapidly over recent decades into a technique for systematically identifying the resource flows and environmental impacts," (Horne, Ralph, Grant, & Verghese 2009). LCAs have become so popular because they look at a product or service from 'cradle-to-grave.' Moreover, LCAs examine many externalities that generic studies overlook, such as impacts seen extracting the raw materials required, transporting the product, or reusability. Because LCAs look from beginning to end, there is also opportunity to account for interaction between phases of the life cycle that may decrease a bags environmental impact. Lastly, LCAs are favored due to their ability to filter out public sentiment; "This approach aims to get rid of public perception-related inclinations and subjectivity, activist group views, and other non-scientific factors," (Horne et al. 2009).

Even with a standardized approach, there is still much disagreement over which type of bag is best. LCAs follow a structure with four phases: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment, and Interpretation. During the Goal and Scope Definition phase, "the fundamental concepts of the study are specified within the framework of the standard," (Klopffer & Grahl 2014). In other words, a framework is defined that limits the scope of the study. The following phases must evaluate the product only within the defined scope. With differing scopes, there can be variations in conclusions as well as the severity of those conclusions.

Despite the practicality of LCAs in offering a standardized approach, they are still a fairly new introduction to the science world. In the literature reviewed for this study, there was no discovery of an LCA study comparing paper, plastic, and reusable cotton bags directly to one another. One LCA study did evaluate all types of bags but added an avenue in addition to eco-friendliness: functionality. These scholars tested what they called *eco-functionality* in which they observed the eco-friendliness in conjunction with how functional the bag was by testing its functionality through a series of weight bearing and reusability tests (Muthu et al. 2012). The conclusion of the study led to plastic and paper bags as being the most eco-friendly and functional for single-use bags whereas woven bags were the best for reusable bags. By making slight modifications in frameworks, plastic, paper, and reusable bags were not compared with one another but rather in separate categories. Moreover, the functionality aspect of the environmental assessment may have changed the results from if it had been purely environmental, though there was not enough information given for this to be determined.

There was another LCA performed on the use of paper and plastic bags that did not include reusable bags published in the Journal of Fiber Bioengineering and Informatics in March 2009. This study, though dated, found that plastic bags are a bit better “in terms of environmental impacts compared to paper bags,” (Muthu et al. 2009). The variables evaluated in this study were radiation & ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, and minerals & fossil fuel. Plastic bags were found to be better in the categories of ecotoxicity, acidification/eutrophication, and land use, or three of the five categories tested.

Even without the use of LCAs, there has been a lot of research done and opinions formed over which type of bag is the most eco-friendly with strong feelings on the side of both plastic and reusable bags.

The first argument that will be explored supports the use of plastic bags as the most eco-friendly. Aside from the LCA described above comparing plastic with paper bags, much of the research compares plastic with reusable alternatives. Since their introduction in the 1970s, plastic bags have been used for a multitude of activities: shopping, trash lining, and packing, to name a few. Their versatility and strength for such little material has proven to be a true innovative wonder.

To produce these standard shopping bags using film extrusion, oil must be burned which emits "toxic gases like dioxins, furans, mercury, and polychlorinated biphenyls (better known as BCPs) into the atmosphere, and pose a threat to vegetation, human and animal health," (UN Environment 2019). Though toxic fumes are released in this process, it is argued that production of plastic bags is more eco-friendly than the production of other bags in using less water and releasing fewer greenhouse gases. Even better, the HDPE bags are "manufactured from a by-product of the gas and oil industries. These bags could be wildly beneficial in terms of reducing global warming because there are no new resources that need to be acquired," (Musa, Hayes, Bradley, Clayson, & Gillibrand 2013). In other words, while resources need to be grown directly for the manufacturing of reusable bags, the by-product used to create HDPE bags is already there and would go to waste if not made into the bag. That said, it is important to note that there are wide ranges of estimates for how many times a cloth bag must be reused to equate to one plastic bag, ranging from the hundreds to thousands of times used. This inconsistency highlights the wide range of disagreement in this topic of study.

Aside from disputes over how many times a cloth alternative must be reused, there is the question of whether or not reusable bags are even used in the first place. While many Americans own reusable bags, many forget their bag at home which "indicates that the behavior is not routine for most people and may be inconsistent between trips," (Karmarkar & Bollinger 2015). Is purchasing a bag that is never used (and that used up resources to be created) going to be better for the environment than a plastic bag? Further, the literature researched has pointed out the implications of using reusable bags: American households will no longer possess the infamous "bag of bags." In fact, in 2007, when a grocery/retail plastic bag ban went in effect in San Francisco, sales of "still legal, low-density polyethylene plastic bags shot up 400%" in place of the free bags no longer being available (Mangu-Ward 2015). These other types of bags, "such as bin liners and disposable nappy bags, contribute as much or greater impact to the environment, especially considering the resources needed in their production and cost more to transport due to their heavier weight," (Musa et al. 2013). Of course, it should be noted that the statistics used in this field can be a bit misleading. 400% could mean an increase from 10 units sold to 50 units sold, or 100 units to 500 units. These are severely different unit increases that have the same percentage increase. The lack of clarity and meaning that can be drawn from some of the statistics used in studies points again to the need for the use of a standardized process to draw more meaningful conclusions.

In most recent news, states are reviewing bans on plastic bags for cleanliness purposes. With the COVID-19 epidemic sweeping the nation, The National Review noted that San Francisco, New Hampshire, Massachusetts, and Maine have all modified their ban on plastic bags for the purpose of reducing transfer of the virus (though there is no known scientific discovery to back the validity of this decision). That said, "plastic bag bans were associated in one study with a 46% increase in death from food-borne illnesses," (Smith 2020). Essentially, when consumers purchase meat at the grocery store and transport it home using their reusable bags, the juices seep into the cloth and bacteria feasts on it. Most people do not think to wash their reusable bags but "if (they) do, (they) generate more carbon emissions by using the washing machine than (they) would have produced by simply manufacturing a fresh plastic bag," (Smith 2020).

While there is some variation in the reasoning towards plastic bags being superior discussed thus far, there is a lot of debate in the literature over which type of bag is best in terms of its disposal or end of life action. This is where the argument towards plastic bags begins to falter. Recycling is considered an eco-friendly option of disposal. Plastic bags can be recycled and reused, though 96% are being thrown in landfills (Muthu et al. 2009). In fact, "an estimated 90.5% of plastic produced since 1950 is still in existence," because not only is it not generally recycled, but it also does not break down (Walt 2020, 6). In 2017, "only 8.4% of plastic waste in the U.S. was recycled and an additional 15.8% was burned to generate energy; the rest wound up in landfills," (Walt 2020, 6). Most of the plastic the United States recycled was shipped to China. However, in 2018, China launched a ban called "Operation National Sword" which banned the importation of plastics to be recycled. "Many polymers that users try to recycle are too low-grade for manufacturing. Soiled and damaged plastics often can't be repurposed. And the price pressures created by the virgin plastic have only disputed things further," (Walt 2020, 15). This indicates that plastics were arriving on Chinese soil that could not be recycled, leading to a lot of waste that did not originate in country but polluted it just the same. Further, there is no longer an economic benefit to recycle plastics. Thus, the infrastructure the United States once used has been inhibited by Operation National Sword. In 2021, it is expected that single-use plastics, such as plastic bags, will be "strictly controlled in the EU's 27 countries, and plastic bags will be banned in major cities in China" (Walt 2020, 20). Meanwhile, the United States only has 8 states that have banned single-use plastics.

If recycling of plastic bags does not take place, they are commonly burned in open fields which is a large contributor to air pollution. "12% of most municipal solid waste is made up of plastic of one kind or another and about 40% of the world's garbage is burned," (UN Environment 2019). The burning of plastic has severe implications from the byproducts settling on crops and waterways to causing cancer and increasing the risks of other illnesses (UN Environment 2019). Further, "when burnt, these bags emit dangerous air pollutants and when dumped in landfill sites, their long decomposition process comprising toxic chemicals leaches into the ground, polluting ground water reservoirs," (Bharadwaj, Baland, & Nepal 2020). Even more alarming, even if plastic bags are recycled, the plastic must still be remelted for reuse meaning toxic fumes are emitted either way (Gibson 2020).

While the end-of-use term for a plastic bag seems to be worse than reusable alternatives, there are still advocates for the plastic bag. One LCA study, conducted by Muthu, found that "the eco-impact of plastic and paper bags was very high if there were no usage and disposal options provided," (Muthu et al. 2009). In other words, when there are re-use or proper disposal techniques provided for the plastic bags, their eco-impact drops. Carrying this logic, if a plastic bag is less environmentally taxing to produce than a reusable bag and has disposal options other than the garbage, it may become a competitive alternative. However, the likelihood of this coming to fruition is slim. One researcher, Mangu-Ward, points out that "in 2010, according to the U.S. Environmental Protection Agency, Americans threw away 690,000 tons of HDPE bags. Of those, approximately 30,000 tons were recycled. That means a total of 660,000 tons were discarded, mostly into landfills (approximately 82 percent of non-recovered municipal solid waste goes to landfill; 18 percent is incinerated)," (Mangu-Ward 2015). While this seems to speak against plastic bags, Mangu-Ward then goes further to say that "that same year, Americans also chucked almost exactly the same amount of 'reusable' polypropylene bags (680,000 tons), of which zero were recovered. In other words, those polypropylene reusable bags actually constituted a slightly higher proportion of bags going into landfills." While polypropylene is another type of plastic reusable bag and not the cotton this study will be examining, the comparison is interesting to consider in future research.

It was also noted in Muthu's LCA study that paper bags have less of an environmental impact depending on how they are disposed. Paper bags can be recycled to create corrugated cardboard. However, much like with the practicality of recycling plastic bags, the paper cannot be wet or damaged like many bags end up after a trip to the grocery store. Further, even if the bag can be recycled, there is question as to how many people perform the action.

Cloth bags can also be recycled, though recycling cotton is a difficult, environmentally taxing process. Even still, a reusable bag does not undergo the same scrutiny in terms of recyclability as, theoretically, it should be used regularly and thus not require the same end-of-life action as a single-use alternative. Once recycled, cotton is much more useful than paper or plastic alternatives. "Recycled cotton consists of reclaimed organic and traditional cotton "scrap" which is spun into new yarn," (Canadian Plastic Bag Association 2019).

This leads into to the other side of the argument: reusable bags are superior to plastic bags. Some of the arguments made for reusable bags are in relation to what reusable bags do not do that plastic does. For instance, "in the absence of recycling efforts, the ubiquitous nature of plastic bags contributes to a host of interrelated development concerns," of which some such consequences have already been discussed (Braun). One researcher who did work in Mali points out that "the proliferation of plastic bag garbage in the environment poses health risks to cattle, sheep, and other livestock who ingest plastic bags littered in the streets and may die as a result of the obstruction in their digestive systems. Plastic bags also wash into rivers, threatening aquatic wildlife or blocking drains and causing floods that may damage people's homes and crops. Plastic bags also hold rainwater and easily become a breeding ground for mosquitos, which increases the risk of malaria," (Braun & Traore 2015). These consequences of plastic bag usage are not seen with reusable bags and thus many advocate for their use. Moreover, plastics never truly go away. "Although plastics photodegrade and break apart, they do not biodegrade. That is, the pieces may get smaller and smaller, but they do not turn into something else," (Decker 2012, 351). There are studies being conducted on bacteria that could break down plastic and negate some of this argument. For the purpose of this study, the information relating to these bacteria is too recent to see the full effects and is thus ignored.

Reusable bag advocates also argue that studies that promote plastic as the superior bag are incorrectly done. That is, their time span is too narrow. While many argue that the production process for plastic bags is more eco-friendly, the disposal period is not considered correctly. “When assessing the performance of landfills related to concerning global warming potential, it is essential to consider the necessary timeline. Plastics degrade slowly; therefore, a period of several hundred years should be used to include all of the emissions resulting from degradation. Most LCA studies consider a 100-year period and therefore underestimate the contribution to global warming from the degradation of plastic carrier bags,” (Musa et al 2013). In fact, plastic bags take between 400-1000 years to breakdown, and as was just noted, particles will always remain (Musa et al 2013). This underestimation of the disposability time period has been argued to heavily counteract statements advocating for plastic bags.

In all, much of the literature advocated for plastic bags over reusable alternatives, with paper bags variably appearing in the discussion. A synopsis of the literature researched has been provided in the Appendices (Appendix A). To summarize, much of the argument for the plastic bag relies on the manufacturing process and less on the longevity and reusability processes. Reusable bags are deemed to be better in this arena. The question that seems to charge the debate, therefore, is whether or not the extra manufacturing waste warrants the end-of-life results. In a more general sense, there are two large schools of thought that have emerged in the environmental field that come to head in the bag discussion: linear versus cyclical thinking.

Linear thinking is a bit tunneled towards immediacy and economic reliability with little interference from other avenues. This is the side that tends to believe in plastic bag use. Cyclical thinking looks at long-term relationships and responsibilities human beings share with the earth. “Within this understanding is a clear sense of birth and rebirth and a knowledge that what one does today will affect one in the future,” (LaDuke 1994). These thinkers tend to consider longevity and the long-term consequences of actions over the short-term gratification that linear thinkers seek.

PROJECT GOALS

Having done my own research on which type of bag was best to use, I was not satisfied with my findings. Though there will always be multiple sides to every argument, I did not find that either side of the argument properly accounted for all avenues. That is, each study arrived at their conclusion by looking at isolated variables. However, in a field such as environmental studies, there is always interaction that I found these one-sided studies did not account for. Even with the framework of an LCA, there is variability in conclusions by slightly modifying the scope and goals. From this emerged my goal of being able to build a model that showed which type of bag was best for the environment across all stages of the life cycle, accounting for interaction between life cycle phases. I used ideas from the LCA framework and from studies conducted to come up with variables that can be used to measure eco-friendliness. The difference in my work lays in comparing each type of bag (paper, plastic, and reusable cloth) as opposed to just plastic and reusable, and searching for interactions that may modify a bags eco-friendliness across all phases of its life cycle in a standardized way.

Thus, I reevaluated the questions that had led me to do this research and came up with the following questions to address in my own study.

- Can a model be created that assesses a bag's eco-friendliness for comparison across types?
- Which variables should be used to test a bags eco-friendliness?
- Is there interaction between these variables?
- How can the model be user-friendly? That is, how can this model be usable for the average consumer?

In constructing a model such as this, there are many variables that were out of the scope of my time, budget, and ability. Thus, my goal was to build out a working model that could be expanded upon with future research. With that said, I wanted to find at least one variable that addressed each phase of the life cycle: pre-use, use, and post-use.

METHODOLOGY

Finding the answer to these questions required use of Interpretive Structural Modeling (ISM) and Analytical Hierarchy Processes (AHP). "ISM is a method which can be applied to a system-such as a network or a society-to better understand both direct and indirect relationships among the system's components," while AHP "can be used to quantify relationships, weigh the significance of different risks, and thus enhance understanding of an organization's overall risk profile," (Gorvett & Liu 2006). In other words, ISM was used to answer which variables should be considered and how they may interact with one another, while AHP was used to confirm which variables should be used and the significance they carry in a quantified model.

To begin this process, I first determined which variables should be considered in the model. ISM suggests asking professionals to determine which risks exist within the system. In the context of my study, the system is bag life cycles, and the risks that exist within are the variables that contribute to eco-unfriendliness. To determine which risks to use, I listed all variables considered across the literature I reviewed (Appendix B). From there, I further narrowed down the list based on variables I believed I could feasibly define and measure given my time, knowledge, and access to resources. I also eliminated variables that seemed to repeat or would create opportunity for vast overlap. This process left me with six variables: Raw Materials, Toxic Byproducts, Decomposition, Reusability, Recyclability, and Carbon Footprint.

An underlying goal in identifying these variables was ensuring that each stage of a bag's life was considered: pre-use, in-use, and post-use, much like in an LCA. That said, variables were not classified to separate life segments in my model as it would discount interaction between them, and some variables are impacted by multiple stages of life and thus would not fit into a single classification (Appendix C). However, the goal was met in that each stage of the bag's life is covered by at least one variable.

I then worked to determine a "Reachability Matrix," which is the second step in ISM. The Reachability Matrix exists to hypothesize the directed relationships among risk factors, where "directed" refers to the direction of the relationship between the variables of interest. In other words, variable A may directly impact variable B, but variable B may not directly affect variable

A, and this matrix showcases these differences. An example of how a Reachability Matrix functions can be found in Appendix D. For this study, the relationships between variables emerged from the literature reviewed and the interactions pointed out there, as well as from a discussion with a Bryant University Environmental Humanities professor, Maura Coughlin. The findings for the Reachability Matrix for this study are explored in the "Findings" section.

Once the relationships between variables were established, I moved on to attempt to build a model through the use of AHP. AHP was chosen for its ability to "allow for consideration of both qualitative and quantitative decision elements," (Gorvett & Liu 2006, 5). In the field of environmental studies, there is a mixture between qualitative and quantitative variables. I wanted a process that allowed for both to exist within a model so that a variable was not excluded solely for the reason that it did not fit a specific type. The following methodology was followed as a result.

1.) Identify variables to be used in a linear model (often done through ISM, as it was in this case)
2.) Determine the significance of each variable
3.) Construct a comparison matrix
4.) Use the comparison matrix to determine the weights of each variable in a linear model
5.) Determine how each variable will be measured and inputted into the model

With variables identified during ISM, I needed to determine the significance of each. In order to determine the significance, each variable was explicitly defined for the purposes of the study. A survey was then sent out to assess the importance the consumer places on each variable when considering eco-friendliness (Appendix E). The definitions of each variable were provided so as to reduce confusion and interpretation differences.

It is important to note that from this data, I was able to find the weight that the *consumer* places on each of the variables when making eco-friendly decisions. This choice was made as I wanted to construct a model that an average consumer could use to make eco-conscious decisions for their specific situation in a standardized way. Therefore, to reflect this decision, the variable's weights needed to be constructed in a way that they reflected consumer's indicated value, which is why the survey seeks to understand how important each variable is in the eyes of the consumer. Once results from this survey were compiled, the comparison matrix was constructed. See Appendix F for an example of how a comparison matrix works.

The comparison matrix, in general, reflects “the relative importance of each pair of risk factors (with respect to their impact on the overall risk value),” (Gorvett & Liu 2006, 8). As made note to above, for this study, this “relative importance” is through the eyes of the consumer. To create the comparison matrix, the mean score of each variable was calculated, and then that score was used to determine the values that appear in the comparison matrix in regard to relative importance. The findings for this matrix will also be discussed in the “Findings” section.

Once the comparison matrix was calculated, the weights of each variable needed to be calculated. This step in the process would also prove if there were variables that did not carry any real significance in the model. To find the weights, we used the following formula:

$$(C - \lambda I) * \vec{v} = \vec{0}$$

Here, C is the comparison matrix, $\vec{v}$ is a nx1 column vector that holds the weights of the variables, and λI is an n x n matric with eigenvalues $\lambda_{1,\ldots,n}$ along the diagonal and zeroes off the diagonal. The goal in this was to find the $\vec{v}$ matrix. Excel Solver was used to find this matrix.

With the weights of the variables calculated in accordance to the aforementioned methodology using the data from the survey, I then worked to find ways to measure each variable. This was done through extensive research. The underlying goal of working to measure each variable was in ensuring the values fell along the same scale so as to produce an index of possible outputs. This index allows for standardization and for comparisons across bag types, which was the ultimate objective of this research.

FINDINGS

Definitions of each Variable:

Before all of the research could be conducted, each variable had to be defined. The definitions of each variable are listed on the next page.

Variable	Definition
R1~Raw Materials	Measures material input, whether it be paper, plastic, or cotton
R2~Toxic Byproducts	Measures how many toxic byproducts that effect life (with a focus on land) are given off by each type of bag throughout the entirety of its life
R3~Decomposition	Refers to how easily the bag will breakdown after use
R4~Reusability	Measures how often a single bag can be reused
R5~Recyclability	Refers to the ability or disability (or ease) of recycling a bag
R6~Carbon footprint	Refers to the amount of greenhouse gases emitted into the atmosphere throughout the life cycle of the bag

Figure 1: Definitions of Variables

Interaction Amongst Variables:

The objective of this research was to answer four questions, the first of which was whether or not these variables interact with each other. The Reachability Matrix on the next page portrays the relationships found during the ISM evaluation.

		Raw Materials	Toxic Byproducts	Decomposition	Reusability	Recyclability	Carbon Footprint
	1	0	0	0	0	0	0
Raw Materials	1	1	1	1	1	1	1
Toxic Byproducts	1	0	1	0	0	0	1
Decomposition	1	0	1	1	0	1	1
Reusability	1	0	0	0	1	0	1
Recyclability	1	0	1	1	0	1	1
Carbon Footprint	1	0	0	0	0	0	1

Figure 2: Reachability Matrix

Note that in using a Reachability Matrix, a 1 indicates that there is a directed relationship between the variables in that the row variable directly impacts the column variable.

Raw Materials: Raw materials directly impacts each variable.

- Raw materials impact toxic byproducts. Depending on the raw materials used, the byproducts it can and will give off will be different.

- Raw materials impact decomposition. Depending on the raw materials used, it will decompose accordingly.
- Raw materials impact reusability as the materials used dictate how sturdy the bag is.
    - EX: Paper is less reusable than cotton and plastic.
    - Note that this is being assumed for this study as we are not considering mixed blends. This relationship will likely change if blends are worked into the model.
- Raw materials will impact how recyclable something is.
    - EX: If it is made from plastic, it will be less recyclable then a more natural material.
- Raw material will impact carbon footprint. Depending on what is used to make the bag will dictate which gases it gives off in all stages of its life.

Toxic Byproducts: Toxic byproducts directly impacts carbon footprint, but no others.

- Toxic byproducts do not impact raw materials. No matter what byproducts are given off, the bag has already been made so it cannot impact what it was made with. While toxic byproducts may be considered by some bag manufacturers before they make the bag when choosing the material, this speculation will be ignored in the model.
- Toxic byproducts do not impact decomposition. What the bag gives off in toxic byproducts will not dictate how it will decompose, or how easily it will decompose.
- Toxic byproducts do not impact how reusable something is. A bag could be very reusable but be made from any material, and in turn give off any toxic byproduct. The only thing reusability *may* do is delay the byproducts given off at the end of life.
- Toxic byproducts do not impact recyclability. Whether or not you can recycle a bag is not impacted by the toxic byproducts it will give off. It may make recycling more green if less toxic byproducts are given off, but it will not dictate whether or not it is recyclable.
- Toxic byproducts do impact carbon footprint. As these byproducts leech into the ground during any phase of the process (production, in-use, decomposition), will impact the gases given off.

Decomposition: Decomposition directly impacts toxic byproducts, recyclability, and carbon footprint, but no others.

- Decomposition does not impact raw materials. A bag decomposes long after raw materials are chosen so unless it is considered in the mind of the manufacturer, which we are ignoring, it would have no impact.
- Decomposition does impact toxic byproducts. How a bag decomposes and how easily that process is done will impact what is given off for toxic byproducts.
- Decomposition does not affect reusability. How easily a bag decomposes does not affect whether or not it can be reused.
    - EX: a plastic bag could be used as many times as a paper bag, but this does not dictate that the plastic is not decomposable while the paper is.
- Decomposition does impact recyclability. How easily a product can be broken down will impact whether or not it can be recycled.
- Decomposition does impact carbon footprint. As it decomposes, products can release GHG which would increase carbon footprint.

Reusability: Reusability does not impact any variable except carbon footprint.

- Reusability does not impact raw materials. Raw materials are picked long before a bag is put in the position to be reused.
- Reusability does not impact toxic byproducts. Just because a bag is reusable, it can be made from a plethora of different materials which can give off any different number of toxic byproducts.
- Reusability does not impact decomposition. Though a bag that is reusable is arguably made from thicker and more durable materials that will be harder to decompose, those materials could still range from plastics to natural materials which would decompose very differently and fall more to what the bag is made from then it would the fact that it was reusable. Moreover, a cotton bag is just as reusable as a thick plastic bag but would decompose very differently.
- Reusability does not impact recyclability. Same reasoning as above. Just because the bag can be reused does not say whether or not it can be recycled as the material it is made from will still vary.

- Reusability does impact carbon footprint. Generally, the more reusable something is, the more durable the bag has to be and thus a more strenuous manufacturing process is required that will impact the carbon footprint.
  - EX: even within just a plastic bag, the more reusable it is, the thicker the material and thus the more emissions given off in manufacturing and decomposition.

Recyclability: Recyclability directly impacts toxic byproducts, decomposition, and carbon footprint, but no others.

- Recyclability does not impact raw materials. Raw materials are selected long before a product is recycled. Again, unless the manufacturer considers whether it is recyclable and picks materials accordingly, there is no direct relationship (which is in line with what this model is assuming).
- Recyclability does impact toxic byproducts. If a product is not recyclable, it may give off more toxic byproducts, or even if it is recyclable, the process of recycling may impact which type of byproducts are given off or lessen the toxic byproducts that would have been given off had the bag not been recycled.
- Recyclability does impact decomposition. If a bag is recycled, it will impact how it decomposes.
- Recyclability does not impact reusability. Just because a bag is recyclable does not mean it is reusable. That will fall more to the materials the bag was made of.
- Recyclability does impact carbon footprint for the same reasons it impacts toxic byproducts and decomposition.

Carbon Footprint: Carbon Footprint does not directly impact any variable.

- Carbon footprint does not impact raw materials (unless the manufacturer considers the carbon footprint and selects materials accordingly, but this model is ignoring all intent of manufacturers).
- Carbon footprint does not directly affect toxic byproducts. What the byproducts give off will impact carbon footprint, but what the carbon footprint is will not impact what the toxic byproducts are.
- Carbon footprint does not impact decomposition. Same reason as toxic byproducts.

- Carbon footprint does not impact reusability. The gases given off by the bag do not impact whether or not it can be reused.
- Carbon footprint does not impact recyclability. Same reason as toxic byproducts.

<u>Construction of the Model:</u>

The actual construction of the model did not require the use of this Reachability Matrix or noted relationships above, but they are still important to consider; the exercise of creating the matrix helps call to mind the complexity of these variables and quantifying them in a model, showing there is a lot of room for future research and discussion. Nonetheless, I was successful in building a model around these six variables.

As noted, after the variables were determined through the ISM process, I worked to determine the significance of each variable based on consumer input. A survey was sent out asking individuals to rate, on a scale of 1-7, the importance of each variable when considering a bag's eco-friendliness (Appendix E). With a total of 58 responses, the mean score was calculated for each variable. The data from this survey is included on the next page.

Score	Raw Materials	Toxic Byproducts	Decomposition	Reusability	Recyclability	Carbon Footprint
1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.00%	0.00%	0.00%	3.45%	0.00%	0.00%
3	3.45%	0.00%	1.72%	1.72%	5.17%	3.45%
4	6.90%	0.00%	8.62%	1.72%	6.90%	5.17%
5	18.92%	5.17%	12.07%	20.69%	25.86%	10.34%
6	27.59%	24.14%	22.41%	15.52%	20.69%	22.41%
7	43.10%	70.69%	55.17%	56.90%	41.38%	58.62%
Mean	6.00	6.655	6.207	6.138	5.862	6.276

Figure 3: Survey Data Breakdown

The percentages within each cell indicate what percentage of the 58 people voted for that score for each variable. These percentages were used in calculating the mean score for each variable. These scores were then used in the construction of the comparison matrix. The comparison matrix functions as was noted in Appendix F, but to highlight another example, looking at cell (1, 5), it says that variable R1 (Raw Materials) is 1.024 times more important than R5 (Recyclability) based on this limited sample. In other words, the mean score for R1's importance, or 6.00, is 1.024 times higher than R5's mean score of 5.862. Thus, this matrix is representative of the relative risks among variables per the input of the consumer.

	Raw Materials	Toxic Byproducts	Decomposition	Reusability	Recyclability	Carbon Footprint
Raw Materials	1.000	0.902	0.967	0.978	1.024	0.956
Toxic Byproducts	1.109	1.000	1.072	1.084	1.135	1.060
Decomposition	1.034	0.933	1.000	1.011	1.059	0.989
Reusability	1.023	0.922	0.989	1.000	1.047	0.978
Recyclability	0.977	0.880	0.944	0.955	1.000	0.934
Carbon Footprint	1.046	0.943	1.011	1.022	1.071	1.000

Figure 4: Comparison Matrix

Once the comparison matrix was calculated, I was able to begin the process of finding the indicated weights for each variable. It is important to note that the mean scores and corresponding comparison matrix show that consumers value each variable relatively equally, so we should expect the weights to be close together.

To find the indicated weights, I used AHP, which is represented by the following formula that was outlined above:

$$(C - \lambda I) * \vec{v} = \vec{0}$$

The comparison matrix, C, is now solved for. The next step is to subtract the λI matrix from the comparison matrix. In this matrix, the λ is the maximum eigenvalue of the comparison matrix. AHP calls for the λ to be the maximum eigenvalue as that is the one eigenvalue that properly indicates the relative importance of each of the factors per the equation (Saaty). Using an eigenvalue calculator, six eigenvalues were outputted for the comparison matrix, of which 6 was the maximum. Thus, λ is equal to 6. Subtracting the λI matrix from the comparison matrix yields the following results:

	Raw Materials	Toxic Byproducts	Decomposition	Reusability	Recyclability	Carbon Footprint
Raw Materials	-5.000	0.902	0.967	0.978	1.024	0.956
Toxic Byproducts	1.109	-5.000	1.072	1.084	1.135	1.060
Decomposition	1.034	0.933	-5.000	1.011	1.059	0.989
Reusability	1.023	0.922	0.989	-5.000	1.047	0.978
Recyclability	0.977	0.881	0.944	0.955	-5.000	0.934
Carbon Footprint	1.046	0.943	1.011	1.022	1.071	-5.000

Figure 5: (C - λI) matrix

Now, per the formula, the only unknown in this equation is $\vec{v}$, which is representative of the weights of the model. To solve for $\vec{v}$, I used Excel Solver. Essentially, Solver outputs solutions that meet an inputted set of criteria. Solver was instructed to have $(C - \lambda I) * \vec{v}$ equivalent to the zero matrix per the constraints of the equation. Additionally, the solutions I wanted for $\vec{v}$, because they were weights for a model, was the eigenvector whose values summed to one. Solver then found the solution that fit the criterion. A graphic of the output is placed below. The Solver approximation column notes how closely Solver was able to have $(C - \lambda I) * \vec{v}$ equate to the zero matrix; the values are all very close to zero as they should be. The highlighted numbers showcase what was found for $\vec{v}$.

$(C - \lambda I)$						Solver Approximation	=	0 vector
-5.000	0.902	0.967	0.978	1.024	0.956	-6.7E-16	=	0
1.109	-5.000	1.072	1.084	1.135	1.060	8.16E-15	=	0
1.034	0.933	-5.000	1.011	1.059	0.989	-7.2E-16	=	0
1.023	0.922	0.989	-5.000	1.047	0.978	-7.2E-16	=	0
0.977	0.881	0.944	0.955	-5.000	0.934	-4.6E-15	=	0
1.046	0.943	1.011	1.022	1.071	-5.000	-7.8E-16	=	0
0.16156	0.17920	0.16713	0.16527	0.15785	0.16899	1	=	1

Figure 6: Finding $\bar{v}$ using Solver

This solution indicates that the model should be constructed as follows:

$$Output = 0.16156 * RAW\ MATERIALS + 0.17920 * TOXIC\ BYPRODUCTS + 0.16713 * DECOMPOSITION + 0.16527 * REUSABILITY + 0.15785 * RECYLABILITY + 0.16899 * CARBON\ FOOTPRINT$$

Note that these weights being close together makes sense as the mean score of each per the results of the survey were similar. Similar means suggest that consumers put similar importance, or weight, on each variable, and this model represents that viewpoint. Conducting AHP in this way enabled us to see that each variable withdrawn from the literature has weight in the consumer's mind when making eco-conscious decisions, and thus should all be included in the model.

With the structure of the model constructed and the variables determined, we had to determine how each variable should be measured and what the resulting overall "output" would be and represent. Since this is a model that I wanted consumers to be able to use when they make decisions, I wanted to ensure that each variable was measured in such a way that the average person could find the information needed. Moreover, I wanted the measurement scale to be consistent across variables for ease of understanding. Thus, each variable is measured from 0 to 100. With each variable being measured from 0 to 100, the overall "output" is also scaled from 0 to 100. This creates an index that produces eco-friendliness scores from 0 to 100 that allows for comparison across bag types. I wanted lower scores to signify greater eco-friendliness so that a consumer can strive for zero adverse environmental consequences. In using this index, it is hoped that consumers will have the mindset, "How can I lessen my score, and thus lessen my environmental impact?" With this in mind, the following variable measurement systems were constructed for use in the model.

R1~Raw Materials:

For the sake of this study, there are four inputs for raw materials: plastic, paper, traditional cotton (cotton grown with pesticides), or organic cotton. The time, knowledge, and resources for my study inhibited expansion into blends and instead focused on bags made from each material in isolation. In this way, there will be certain types of bags that will not be accounted for in this model. Future research is required here in expanding on this variable and determining a continuum on which it can be measured.

Given that raw materials influence each of the other variables in the model, it serves to reason that a lot of the eco-friendliness of a bag is determined here; certain bags will be at a disadvantage solely because of the material they are made of. In general terms, organic cotton bags are the best material for a bag to be made from. Without pesticides, harvesting cotton is an entirely natural process, aside from cultivating and farming the lands, but other variables in the model will account for these effects. The next best material is traditional cotton. Again, it is sourced in a natural way, but the pesticides make it a less eco-friendly alternative than organic cotton. The third best material is paper. Paper bags come from natural pulp, but damage must be done to the trees and forests in order to harvest the pulp needed. Furthermore, there are many other chemical inputs into a paper bag to transform the pulp. Thus, though it has origins in a natural source, the addition and damage it causes ranks it third.

Finally, we have plastic bags. Plastic bags are made from a synthetic material. The inputs do not come from natural materials. It was noted in the literature review that plastic bags are often made from a byproduct of the oil and gas industry and thus require less extraction of natural resources from the earth. However, the processes to get to the point of having the byproduct that is then made into plastic is environmentally taxing, and the raw material itself, regardless of origin, is not natural. For these reasons, the model will be proceeding with it as the worst of the raw materials, but there is room for future research here.

Based on this analysis, the following chart represents the variable input for the model. Note that no level of material receives a score of 0 as the creation of any material will have some inherent wear on the earth. The corresponding inputs are on the following page.

Material	Variable Input
Organic Cotton	25
Traditional Cotton	50
Paper	75
Plastic	100

Figure 7: Raw Materials Measurement Scale

R2~Toxic Byproducts:

While there is a plethora of toxic byproducts that can be released in any process, there are a specific set that "are subject to Toxics Release Inventory (TRI) reporting under Section 313 of the Emergency Planning and Community Right-to-Know Act (EPCRA)," (EPA). Within this set of toxic byproducts, there is a subset known as "Persistent bio-accumulative toxic substances (PBTs)" that "are chemicals that do not degrade easily in the environment," (Secretariat of the Commission for Environmental Cooperation). Because they remain in the environment, PBTs have been linked to having an adverse effect on food chains, animals, plant and human health, and climate change (Secretariat of the Commission for Environmental Cooperation). Where the variable "Toxic Byproducts" was defined to measure how many toxic byproducts are given off by each type of bag, using PBTs signals out the worst of the possibilities while also securing better data availability for the consumer as the EPA mandates reports of PBTs. In all, there are 21 PBTs, 5 of which are chemical compounds and 16 of which are chemicals (EPA). The PBTs and reporting thresholds can be found on the EPA's site.

To measure Toxic Byproducts, a consumer will look at the TRI chemical reports and find, of the 21 PBTs reported, which ones are present in the bag they are using. A percentage will then be calculated that will be the input into the model:

$$\frac{Number\ of\ PBTs\ reported}{21} * 100$$

Of course, this negates the differences in the *amount* of each individual PBT present, but for the sake of the consumer's education levels and ease of data finding, the percentage for number of PBTs found will be used. This, however, is an important consideration for future research.

If this data cannot be found, the EPA also has a tool that reports in terms of pounds of TRI chemicals released by factory. This tool can be found on the EPA's Toxic Release Inventory Program page. This tool allows users to look up manufacturing plants and shows how many pounds of release each give off. There are very large ranges provided by the EPA, and some plants manufacture more than bags, so it may not be as meaningful as the aforementioned method, but it is better than not including anything. Moreover, it may be beneficial as it accounts for all chemicals under the TRI program, not just PBTs.

Total Releases by Facility	**Variable Input**
0 lb.	0
> 0 - 100 lbs.	5
101 - 10,000 lbs.	50
10,001 - 100,000 lbs.	75
100,001 – 1,000,000 lbs.	100
> 1,000,000 lbs.	100

Figure 8: Toxic Byproducts Secondary Measurement Scale

No matter what, it is important that the consumer note which methodology they are using in their analysis and that they remain consistent when comparing bag types as the scales will create quite different results.

R3~Decomposition:

Decomposition's input will be a direct numeric insert of how many years it takes for the given bag to break down, from no time at all (which is impossible) to 100 years. Fractional years are permitted. If a bag takes longer than 100 years, a consumer should make note of that in the analysis, but input the cap of 100. It is important to note that nothing mathematically incorrect will happen if a time period beyond 100 years is input, but it could produce a score outside of the index bounds depending on the other inputs. Thus, if the user so desires, they can put in a time period beyond 100 years without fear of breaking the model, but it will result in extrapolated outputs. The cap of 100 was chosen to keep the 0-100 scale consistent among variables and because there is little research to suggest what happens beyond 100 years of decomposition.

It is important to note that there is a lot of opportunity for drastic differences in results as a paper bag could take as little as one month to break down, while a plastic bag could take over 100 years. This brings the argument that no matter how eco-friendly a plastic bag is, it will always lose to alternatives because of how long it takes to decompose. While this is an important note, I have chosen to proceed with this measurement tactic of the variable for two reasons. The first is that because plastic bags are newer, the long-term impacts of their decomposition are still being discovered. This inherent risk must have the opportunity to be absorbed into the model. Moreover, plastic never fully breaks down, whereas the other materials observed in this study (paper and cotton) do. Having this represented in the model will be extremely important as the inability of plastic to break down causes the remaining particles to infiltrate food-chains and ecosystems, causing much more damage that is not measured in other parts of the model. To reflect this unknown risk and damage to human and plant health, the consumer should proceed with this scaling method.

It is important to note that if the bacteria discussed in the literature review are found to be effective on a large scale, this variable will likely see less discrepancy between plastic and paper or cotton alternatives as it will truly decompose like the other materials do.

R4 ~ Reusability:

This variable refers to how reusable a bag is (i.e., how many times it can be reused). Please note that this variable could be used to represent both the *potential* amount of times a bag can be reused or the *actual* number of times it can be reused. Take the case of a cotton bag for example. It *could* be used 200 times, but is *actually* only used once. This will create drastic differences in the variable input, but both may be important to represent. Though a more accurate eco-friendliness score will be generated if the consumer inputs their actual use, either train of thought can be followed, so long as the consumer is consistent across bag types. The table indicating the proper input is displayed on the next page.

Number of Times bag is Used	Variable Input
0-10	100
11-20	90
21-30	80
31-40	70
41-50	60
51-60	50
61-70	40
71-80	30
81-90	20
91-100	10
101+	0

Figure 9: Reusability Measurement Scale

R5~Recyclability:

Recyclability focuses on how easy it is to recycle a bag and will function much like Raw Materials in that it is on a scale. Some materials are simply harder to recycle than others and this variable will represent that.

It should be noted that there are many assumptions made with Recyclability. If a consumer does choose to recycle, the model assumes that the bag will then actually be recycled. This, however, is a very large assumption. Many municipalities do not recycle all types of plastic or other materials, so even if a consumer makes the choice to recycle something, the means by which they can recycle may be limited. Moreover, even if the consumer does properly recycle the bag, there are numerous steps between that point and the actual recycling process that are not always followed. With all of these moving pieces out of the consumers control or ability to find out, we have decided to use a standard discrete entry that looks solely at how easy something is to recycle given that it is to undergo the proper recycling process. The table indicating the proper input is displayed on the next page.

Material	Variable Input
Paper	25
Cotton	50
Recyclable plastics	75
Non-recyclable material	100

Figure 10: Recyclability Measurement Scale

R6~Carbon Footprint:

Carbon Footprint is a measure of Greenhouse Gas Emissions throughout the life of a bag. Greenhouse Gases are those that are capable of absorbing heat and are often attributed to causing temperature increases in the Earth's climate. A Carbon Footprint is representative of these greenhouse gas emissions and is given in terms of grams (or another unit of weight) of carbon dioxide. Though carbon dioxide is not the only greenhouse gas, all other greenhouse gases' mass are converted to carbon dioxide so that one standardized score can be used.

Virtually every process or product has a Carbon Footprint score attached to it, but the ease of finding it can vary. One book, "How Bad Are Bananas?", gives the Carbon Footprint for plastic bags and reusable bags, though it does not give the materials of which the bag is made from. If a user is unable to find a carbon footprint score in their own research, they can use the estimates presented in this book. This book can be found on Amazon.

It is important to note that carbon footprint can be noted in terms of multiple units of weight measurement and across different times lines. For instance, it may be noted that one singular plastic bag has a carbon footprint of X grams, but it could also be written that using one plastic bag every day for a year is X pounds. This model is constructed to account for the single bag and in terms of grams as that will best fit in the 0-100 scale. That said, it is not inaccurate to put in carbon footprint scores on an annualized basis, or in different weights, so long as it is noted in the consumer's use of the model. It may also give scores outside of the range of the Index Score. Again, the model is not built to work like this so the score may be extrapolated, but it will not be mathematically incorrect.

With the scale and weight of each variable determined, the model is now fully constructed. To use the model, a consumer will go through and input the values that are representative of their bag in the input column. The variable score will then be computed based on the input by multiplying the score by its corresponding weight. Once this process is complete for each variable, the results will be summed together to produce the index, or eco-friendliness, score.

Variable	Variable Name	Weight	Input	Variable Score
R1	Raw Materials	0.16156		
R2	Toxic Byproducts	0.179201		
R3	Decomposition	0.167131		
R4	Reusability	0.165274		
R5	Recyclability	0.157846		
R6	Carbon Footprint	0.168988		
			INDEX SCORE	

Figure 11: The Finalized Model

This index score is then a standardized output by which consumers can compare bag types. This model does not have an associated range in which values are "good" or "bad", as those determinations are very subjective, but the lower the score the better. The same is true for within each individual variable as they are scaled on the same basis as the index. Consumers that want to be more eco-friendly should focus on lowering their score as much as possible.

With the creation of this final model, the final two questions we set out to answer are complete: Which variables should be used to test a bags eco-friendliness? Can a model be created that assesses a bag's eco-friendliness for comparison across types?

<u>ANECDOTAL USE OF MODEL</u>

With the variable scaling and the construction of the model detailed, it is important to consider its use. It is important to understand that this model operates based on the specific situation of an individual consumer. This is to say that though the model can be used to help consumers make educated decisions about their individual situation, sweeping conclusions about which type of bag is definitively best cannot be made. To illustrate this and show the actual applicability of the model, we will explore an anecdotal use of the model.

Consider a consumer from the state of Maine using this model to determine the Eco-Friendliness Score of a plastic bag. Looking first at Raw Materials and Recyclability, the consumer would directly input values based on the respective scales. This means that the input for Raw Materials would be 100, while Recyclability would be 75. The remaining four variables require more research and consumer decision making.

Starting with Toxic Byproducts, a consumer can use the EPA's TRI locator to find TRI facilities in their area. For instance, one TRI facility that produces plastic resin, a material used in plastic bag manufacturing, is located in Lewiston, ME. Based on a 2017 EPA Report for this facility, the consumer found that over 1,000,000 pounds of toxic byproducts that must be reported under the TRI program were emitted. Thus, the consumer found the corresponding input for this variable to be 100. Note that there is some room for consumer error and interpretation here. The model relies on the consumer correctly identifying a facility that manufactures plastic bags, and more specifically, the manufacturer that produced their specific plastic bag. For this consumer, how likely is it that their bag came from this facility? Is there a way they can find out? How much of the toxic byproducts released from the facility are for plastic bag manufacturing, versus other manufacturing? This model simplifies that all byproducts are from bag manufacturing, and moreover, makes the assumption that the facility the user found is the correct one. However, it is worth asking these questions.

Looking next at Decomposition, there are numerous scholarly articles containing estimates for how long it takes a plastic bag to decompose. Again, the consumer's influence infiltrates the model in that they must determine which of the estimates they find most accurate. The consumer in this example input 100 for decomposition as they wanted to account for the risk in plastic bags never fully breaking down. A different consumer may have put something lesser, if they consider a bag to be fully decomposed when it is particles of what it once was.

Moving onto reusability, the consumer selected 100 as an input as they plan to reuse the bag once for a trash-bin liner. Lastly, the carbon footprint for any item can be calculated. This consumer looked into the book "How Bad are Bananas?" listed in the section above and found that plastic bags have a carbon footprint of 10 grams.

With all of the numeric inputs, the consumer used the model and the Eco-Friendliness Score was calculated:

Variable	Variable Name	Weight	Input	Variable Score
R1	Raw Materials	0.16156	100	16.156
R2	Toxic Byproducts	0.179201	100	17.920
R3	Decomposition	0.167131	100	16.713
R4	Reusability	0.165274	100	16.527
R5	Recyclability	0.157846	75	11.838
R6	Carbon Footprint	0.168988	10	1.690
			INDEX SCORE	80.845

Figure 12: Consumer Use of Model

A score of 80.84 is arrived at. The consumer could then repeat this process with the other bag types. This consumer chose to do so in order to make a decision about which type of bag they should use. The inputs and calculations can be found in Appendix G, but a summary of the scores is produced in the table below.

Bag	Score
Traditional Cotton (Reused 101+ Times)	50.87
Paper	64.04
Traditional Cotton (Reused 0-10 Times)	67.40
Plastic	80.84

Figure 13: Scores for Various Bag Types

Thus, based on this consumer's individual situation, a traditional cotton bag reused over 101 times is the best. However, if they do not plan on reusing the bag, they should consider paper alternatives. Of course, it is important to reiterate that these scores are indicative of the individual's situation. Following through the consumer journey in finding the score for the plastic bag shows this reliance on individual behavior and further points to this model's inability to make a conclusion that extends to all circumstances.

FUTURE RESEARCH

Though this research and methodology was successful in creating a model, there is still much research to be done. I have already outlined some of these opportunities for future research, but it is important to consider them in further detail.

First, this model largely ignores the likelihood of things happening and focuses instead on how they should happen. For example, just because something should take 1 year to decompose, does not mean it will. Various factors such as exposure to sunlight impact how quickly something decomposes, and if it is in a landfill and gets covered by other trash, it may take longer. Another example is in recyclability. Just because something is easily recyclable does not mean that it will be recycled, even if the consumer places it in a recycling bin. Contamination and inefficiencies in the recycling system are just two examples of possible interference in which something that should happen does not. This model could be strengthened if it took into account likelihoods of each variable input occurring, as the way it stands now is largely representative of theory.

Second, some of the variables were measured in discrete forms and were equally distanced from one another. For example, with recyclability, each material was evaluated for ease of recyclability, ordered, and then spaced equidistant from the prior. This was also done with raw materials. Yet, do the discrete forms really represent the variable as well as they could? Further research could transform this discrete scale into a continuum that allows for other bag types and more accurate representations between the severities of how much better or worse one bag is versus the other.

Lastly, this model relies on a lot of simplification overall. First and foremost, it was simplified to allow for variable inputs to be easily found by consumers, but is this data truly indicative of global impact? The model relies on decisions that are made on a consumer level coming to fruition in order to be accurate. Moreover, an experts' opinions over which variables are most indicative of eco-friendliness may differ from those the consumer indicated consideration for; the weights determined for the model may be less indicative of true environmental impact when looking beyond the eyes of a consumer. This model takes into account the literature cited and the viewpoints of some consumers, but it is not comprehensive of a true global perspective or of all the research that exists today. These variables, through quantifiable, are subject to large interpretation and discussion, which is in part a large reason why a model like this did not exist before.

There are many layers and intricacies that this model does not consider and I feel they are extremely important to note. Some of these intricacies have been noted above, but it is likely that the reader questioned the validity of some of the conclusions made here as their experiences, knowledge, and opinions differ. As noted before, linear thinkers have a tendency to put an emphasis on numbers and follow them blindly, but trying to construct this model has shown just how hard it is to quantify all of these relationships without making large simplifications and assumptions. If anything, it is my hope that this model shows that there is a way to quantify these relationships, but it is in no way indicative of *everything* that influences eco-friendliness of a bag. Future research should be done to really flesh out these simplifications if it is to be relied on beyond the perspective of an induvial consumer.

APPENDICES

Appendix A: Synopsis of Research Conducted

Title	Purpose	Conclusions	Stance Taken?
Studies			
Measures Aimed at Reducing Plastic Carrier Bag Use (Musa 2013)	Collect opinions on recycling HDPE bags, perceptions of alternative bags, view on taxes on HDPE bags	Plastic bags favored with high-risk products, reusable bags are not frequently used, online delivery removes consumer bag choice	N/A
What makes a ban on plastic bags effective? (Bharadwaj et al. 2020)	How bans on plastic bags impact consumer behavior	Growing concern over using plastic bags due to the waste - in particular, how a plastic bag is disposed of (burning, seeping into ground and water)	Reusable Alternatives
Eco-Impact of Plastic and Paper Shopping Bags (Muthu et al. 2012)	LCA performed on eco-impact of paper and plastic bags	Eco-impact of plastic and paper bags is very high is there are no re-use or proper disposal techniques available. With proper disposability in place, the score dropped significantly.	Plastic bags, but dependent on data input

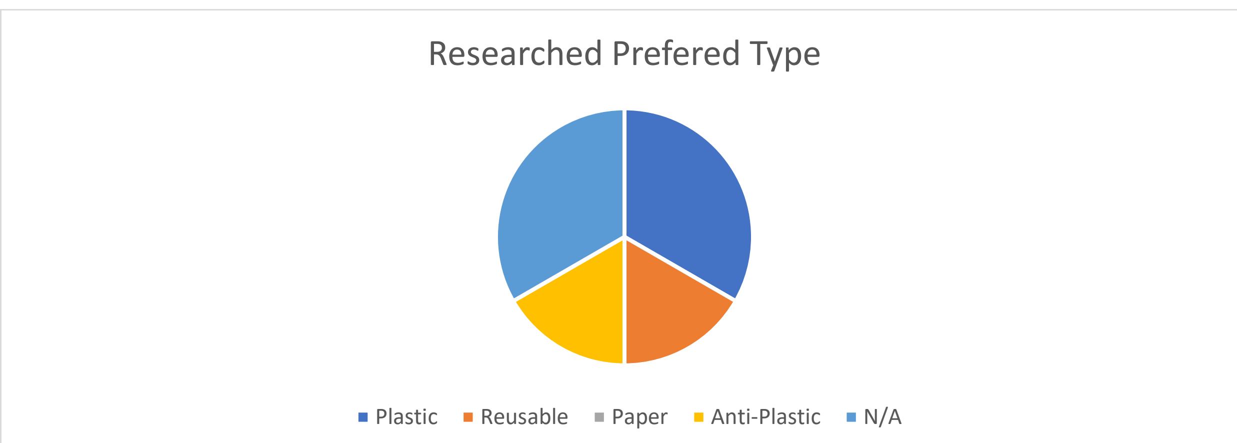
Title	Purpose	Conclusions	Stance Taken?
Studies			
An Exploratory Comparative Study on Eco-Impact of Paper and Plastic Bags (Muthu et al. 2009)	Attempting to infer the environmental concerns made by paper and plastic bags in terms of total amount of energy used by a bag to get it manufactured and amount of pollutants emitted during the manufacturing phase	As far as the energy analysis and pollutants produced, plastic bags perform better than paper bags	Plastic Bag
Plastic Bags, Pollution, and Identity (Braun 2015)	How identity relates to pollution	Plastic bag pollution demonstrates environmental consequences (such as pollution of the body, food system, landscape, etc.) of decision making that has been driven by economic profit with little concern or value for local cultures	Reusable Alternatives
Life-Cycle Assessment (LCA) of Plastic Bag: Current Status of Product Impact (Hermawan 2019)	LCA to evaluate the eco-impact of plastic bags	Plastic bags are environmentally unfriendly due to the harm in manufacturing to both the natural environment and human health	Anti-Plastic, though does not say directly which type of bag is best

Title	Purpose	Conclusions	Stance Taken?
Studies			
Assessment of Eco-Functional Properties of Shopping bags: Development of a Novel Eco-Functional Tester (Muthu et al. 2012)	Trying to develop an instrument that quantifies the eco-functional properties of a bag (i.e., both eco-friendliness and functionality play a role)	Categorizes single use bags and reusable bags separately. Found plastic and paper to be the best single use bags and woven bags the best for reuse	N/A
BYOB: How Bringing Your Own Shopping Bags Leads to Treating Yourself and the Environment (Karmarkar et al. 2015)	Does using a reusable bag impact what consumers purchase in store?	Consumers buy more environmentally friendly foods (i.e., organic) and indulgent foods	N/A

Title	Purpose	Conclusions	Stance Taken?
Articles			
Plastic Bags are Good for You (Mangu-Ward 2015)	Argues that information against plastic bags being less environmentally friendly is faulty and manipulated to work for alarmists	N/A	Plastic bags
Motivating Actions to Mitigate Plastic Pollution (Jia et al. 2019)	Governments need to bring attention to plastic waste and consider consumer behavior in policy intervention		Anti-Plastic, though does not say directly which type of bag is best

Title	Purpose	Conclusions	Stance Taken?
Articles			
Kroger's Feel-Good Ban on Plastic Bags is Worse than Pointless (na 2018)	Makes several arguments for plastic bags including that it has a smaller carbon footprints than cotton bags	N/A	Plastic Bags
Reusable Vs. Disposable Bags: What's Better for the Environment? (Evans 2019)	What is the environmental impact of disposable and reusable bags? When are reusable bags better than disposable bags?	One plastic bag equals 4 paper bags and one cotton bag 173 times.	N/A

Type of Bag	Most Eco-Friendly Bag	Percentage
Plastic	4	33%
Reusable	2	17%
Paper	0	0%
Anti-Plastic	2	17%
N/A	4	33%



Appendix B: Variables Explored in Literature

Source	Variables Examined/Topics Considered
Measures Aimed at Reducing Plastic Carrier Bag Use (Musa 2013)	Resources used (Material inputs), Disposal, Litter
What makes a ban on plastic bags effective? (Bharadwaj et al. 2020)	Air pollution, Decomposition, Toxic byproducts, Pollution
Eco-Impact of Plastic and Paper Shopping Bags (Muthu et al. 2012)	LCA with focus on usage and disposal
An Exploratory Comparative Study on Eco-Impact of Paper and Plastic Bags (Muthu et al. 2009)	Total amount of energy used by a bag to get it manufactured, Amount of pollution emitted during the manufacturing phase of a bag
Plastic Bags, Pollution, and Identity (Braun 2015)	Recycling efforts, Disposal, Health and safety concerns (Animal, human, and plant health)
Life-Cycle Assessment (LCA) of Plastic Bag: Current Status of Product Impact (Hermawan 2019)	Production process, Natural environment and human health, Transportation, Raw materials, Distribution, End-of-Life disposal (This study was an LCA so it evaluates across the entire lifecycle of the bags)
Assessment of Eco-Functional Properties of Shopping bags: Development of a Novel Eco-Functional Tester (Muthu et al. 2012)	Reusability (also evaluates functionality of reuse through strength and weight holding capacity)
BYOB: How Bringing Your Own Shopping Bags Leads to Treating Yourself and the Environment (Karmarkar 2015)	In-store impacts (explored if bag type and types of foods purchased were related)
Plastic Bags are Good for You (Mangu-Ward 2015)	Litter/waste, Animal risk, Reuse (specifically in regards to plastic bags and the "bag of bags"), Recycling
Motivating Actions to Mitigate Plastic Pollution (Jia et al. 2019)	Waste, Life (both animal and human) threats, Soil environment
Kroger's Feel-Good Ban on Plastic Bags is Worse than Pointless (na 2018)	Pollution, Water use, Toxic byproducts, Carbon emissions, Transportation, Disposal

Source	Variables Examined/Topics Considered
Reusable Vs. Disposable Bags: What's Better for the Environment? *Note that this article separates the variables the way I have presented in this exhibit. (Evans 2019)	**Production:** Energy Input, Natural resource use, Transportation, Emissions from manufacturing **Use:** Impact on human health, Lifespan of the product, environmental impact of use **Post Use:** Pollution of natural environment, Emissions from disposal (gasses breakdown in landfill or incineration), Cost of Recycling

Appendix C: Variables across Life Stages

Variable	Pre-Use	In-Use	Post-Use
R1~Raw Materials	X		
R2~Toxic Byproducts	X		X
R3~Decomposition			X
R4~Reusability		X	X
R5~Recyclability			X
R6~Carbon Footprint	X	X	X

This graphic represents when each variable impacts a bags eco-friendliness. For example, Toxic Byproducts impacts a bag's eco-friendliness during the Pre-Use and Post-Use stage of a bag's life. Toxic Byproducts are given off during the manufacturing phase and during the decomposition/disposal phase. Overall, with all 6 variables, each phase of life is accounted for at least once.

Appendix D: Reachability Matrix Example

The following is from Rick Gorvett and Ningwei Lui's paper. It outlines how reachability matrices work. The data in the images and description do not relate to the study conducted here, but simply act as an example to illustrate how the data is converted to and represented by the matrix.

R_1 = age
R_2 = gender
R_3 = location
R_4 = marital status
R_5 = distance driven
R_6 = socioeconomic class

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

where, analogous to Example I, the first row and column refers to the overall risk level, and rows/columns 2 through 7 reflect, in order, the six hypothesized risk factors. For example, the value of one in the (2,5) spot of the reachability matrix above suggests an opinion that age does affect marital status (but not vice versa, as the value in the (5,2) spot is zero). (We emphasize that this matrix, and all the values associated with both the examples in this paper, are for illustrative purposes only; we are not suggesting that these are "correct" or conform to reality.)

To clarify, a "1" represents a directed relationship, and a "0" represents there is no directed relationship. Note that a matrix coordinate system works (rows, columns). In English, it would be read that the variable in the rows position of the coordinate does or does not directly affect the variable in the columns position of the coordinate.

Appendix E: Survey

Eco-Friendliness of Shopping Bags

With numerous types of shopping bags to choose from, consumers must decide which bag works best for them - whether it be reusable, plastic, or paper. One such avenue a consumer may consider when choosing a bag is its eco-friendliness - that is, which bag does the least harm to the environment through all stages of its life. The purpose of this research is to build a model that determines which type of bag is best for the environment.

The following variables/factors will be considered in this model:

- Raw materials: measures mix of inputs in relation to natural versus artificial materials
- Toxic Byproducts: measures how many toxic byproducts that effect land life are given off by each type of bag throughout the entirety of its life
- Decomposition: refers to how easily the bag will breakdown after use
- Reusability: measures how often a single bag can be reused
- Recyclability: refers to the ability or disability to recycle a bag
- Carbon footprint: refers to the amount of greenhouse gases emitted into the atmosphere throughout the life cycle of the bag

Please complete the following survey with the Earth's health in mind - that is land, atmosphere, and climate.

How old are you? *

- ○ 17 and under
- ○ 18-24
- ○ 25-36
- ○ 36-45
- ○ 46 and older

Rate the potential impact the factor RAW MATERIALS has on the well-being and health of the earth. *

	1	2	3	4	5	6	7	
Not at all important	○	○	○	○	○	○	○	Extremely important

The remainder of the survey followed the exact formatting of the 2nd question, but replaced the variable name until all six were accounted for.

Appendix F: Example of Comparison Matrix

The following image depicts another excerpt from Rick Gorvett and Lingwei Lui's paper. This example is purely to illustrate how a comparison matrix works and does not have any data relevant to this study.

$$C = \begin{bmatrix} 1.00 & 2.00 & 4.00 \\ 0.50 & 1.00 & 2.00 \\ 0.25 & 0.50 & 1.00 \end{bmatrix}$$

Each element in this comparison matrix reflects the experts' view as to the relative importance of each pair of risk factors (with respect to their impact on the overall risk value). For example, the value of 2 in the (1,2) spot indicates the opinion that factor R_1 is twice as important as R_2. The opposite side of this pair-wise comparison coin is the 0.50 value in the (2,1) spot, indicating the opinion (consistent with that in the prior sentence) that R_2 is one-half as important as R_1.

Appendix G: Paper and Reusable Bag Examples

(i) Paper

Variable	**Input**	**Source**	**Reasoning**
R1 ~ Raw Materials	75	Discrete Model Scale	Raw material is paper
R2 ~ Toxic Byproducts	100	EPA 2017 Report	Total waste managed in pounds for plant was 2,231,081
R3 ~ Decomposition	1/12 (1 month)	ABC Technology	Quick google search with reliable source
R4 ~ Reusability	100	Discrete Model Scale	Reusability is in 0-10 range
R5 ~ Recyclability	25	Discrete Model Scale	Paper is easiest to recycle
R6 ~ Carbon Footprint	80	“How Bad Are Bananas?”	Carbon footprint for bag made predominately from virgin paper

(ii) Traditional Cotton Bag Reused 101+ Times. All values remain the same for Traditional Cotton Bag Reused 0-10 Times except for Reusability, which raises to 100.

Variable	Input	Source	Reasoning
R1 ~ Raw Materials	50	Discrete Model Scale	Bag made from traditional cotton
R2 ~ Toxic Byproducts	100	Columbia University	Though I could not find an EPA source, all sites (including this one) noted cotton gives off a ton of chemicals
R3 ~ Decomposition	6/12 (half year)	Quora	Cotton breaks down pretty easily
R4 ~ Reusability	0	Discrete Model Scale	Cotton bags from home we have used over 100 times
R5 ~ Recyclability	50	Discrete Model Scale	From model
R6 ~ Carbon Footprint	100	UK Environment Agency	High impact for production of these bags, decreases with times reused

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