BIO-BASED PLASTIC PACKAGING: A TOOL TO HELP ORGANIZATIONS ANALYZE THE TRADE-OFFS BETWEEN BIO-BASED AND CONVENTIONAL PLASTICS

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Abstract

An increasing number of companies are exploring ways to improve their environmental footprint. Some environmental benefits are offered by bio-based plastic packaging; however, this approach requires trade-offs. For example, plastic bottles made with polylactic acid (PLA), a bio-based plastic resin, lack the impact strength offered by plastic bottles made with polyethylene terephthalate (PET). Other trade-offs include diminished shelf life capabilities, increased cost, and recycling infrastructure. In particular, displacement of recyclable plastic packaging with plastics made from renewable resources has created controversy among environmental advocates. Despite its performance, cost, and recycling shortcomings, PLA offers an attractive choice to some because it represents the transition towards use of renewable resources.

In an attempt to address trade-offs, I developed an analytical framework with assistance from key stakeholders. After identifying the fundamental objective of the best choice of resin for the manufacture of plastic bottles, I surveyed stakeholders to create a list of essential packaging criteria, with the three major criteria being performance as a bottle material, cost, and environmental impact. I relied on private interviews with industry experts and conference presentations to gather bottle data for four resins: PLA, PET, high density polyethylene (HDPE) and polypropylene (PP). The framework for comparison was Multiattribute Utility Theory (MAUT), a methodology designed to address trade-offs among multiple objectives to achieve an overall objective.

Based on the survey results and best available data as input for MAUT, PET was the best choice of resin for the beverage bottle. This non-bio-based plastic emerged as the top choice largely due to its superior performance on criteria such as strength and shelf life.

Further analysis of the characteristics of the four plastics showed that even if all environmental and cost characteristics of the bio-based plastic, PLA, were as favorable as any of the other plastics I analyzed, PLA still would not come to the top. Only if PLA's performance as a bottle material (strength, etc.) increased several fold would PLA become the top choice among the four I analyzed. Similarly, analysis of the weighting of the criteria showed that increasing the weights on environmental criteria, compared to performance and cost criteria, cannot elevate PLA to the top choice, mainly because HDPE has desirable environmental characteristics such as recyclability. Only increasing the weight on environmental criteria such as greenhouse gas emissions while decreasing the weight on all other environmental criteria would allow PLA to become the top choice among the four bottle materials I analyzed.

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Introduction

The concept of plastics made from bio-based feedstock such as cellulose or starch is nearly a century old; however, bio-based plastics have only recently become a viable option in packaging applications such as bottles (E.I. du Pont de Nemours and Company 2003). NatureWorks LLC, a wholly owned subsidiary of Cargill, is the first company to commercialize polylactic acid (PLA), a bio-based polymer used in the manufacturer of consumer products such as clothing, bags, and bottles (NatureWorks LLC 2006a).

Recent trends in industry practices reflect a greater focus on sustainability, with particular interest in packaging material that offers improvements in waste reduction and energy conservation. Bio-based plastics offer environmental benefits but also require trade-offs, which has created controversy among environmental advocates. For example, some of the largest not-for-profit recycling organizations, such as Ecocycle in Boulder, Colorado, and Eureka Recycling in Minneapolis, Minnesota, have publicly opposed the use of bio-based plastic in bottles because it threatens the current plastic bottle recycling infrastructure (Institute for Local Self Reliance 2006). Alternatively, municipalities such as San Francisco opt for bio-based plastics over conventional, recyclable plastics through local ordinances that ban all plastic bags except compostable ones (San Francisco Department of Environment 2007). The choice between bio-based versus fossil-resource-based plastic involves many issues beyond recycling and renewable energy, and the complexity is likely to increase as manufacturers consider new technologies (e.g., nanotechnology) that enable bio-based plastics to perform like fossil-resource-based plastics.

For an organization to make informed decisions about a material's environmental performance, it should identify an overall objective (e.g., waste reduction) and the means to that objective. For example, reducing the weight of a package is a means to reducing wasted fuel in transportation, while improving a package's strength reduces spoilage and product waste. Such decisions can be made more effectively with the help of a flexible, transparent decision tool that illustrates all of the key aspects of achieving an overall objective. Use of such a tool elevates the debate about the pros and cons of a material to a constructive discussion about the most important aspects of that common goal: which feature is a company willing to trade for gains in another area? It also enables organizations to focus on development and improvements in areas that have the most impact on reaching the overall objective. Clarifying an overall objective is also a constructive step in overcoming conflicting objectives, which often occur when a variety of stakeholders come together to address an issue.

The goal for this project was to develop an unbiased decision framework to facilitate better choices for packaging given the recent development of bio-based plastics. As nonprofits, government agencies, and forward-thinking companies debate which material is best in the bottle application, I offer a framework for analyzing the environmental and business trade-offs involved in switching from conventional plastics to bio-based or biodegradable plastics for bottles.

Statement of Objectives

My objectives include (1) identification of the top criteria used to select a packaging material through consultation with key contacts in not-for-profits and industry; (2) development of a sample decision analysis tool—an information matrix using Excel—to illustrate the trade-offs between different packaging material types; (3) collection of feedback from packaging industry experts and environmental advocates on the usefulness of the tool; and (4) identification of ways to improve the tool.

Overall, I want to help organizations resolve trade-offs between the advantages and disadvantages of different materials by demonstrating the value of Multiattribute Utility Theory (MAUT), a methodology designed to address trade-offs among multiple objectives to achieve an overall objective (Clemen and Reilly 2001). My decision analysis tool uses MAUT as the decision making framework.

Background

Plastic in Society

Plastics offer a wide range of performance characteristics that have enabled rapid communication and data analysis, advances in medical technology, and energy efficiency. They make possible cell phones, computers, GIS devices, hearing aids, cameras, photovoltaic systems, windmills, insulation, and high-speed trains. In addition to their many societal benefits, plastics create a host of challenges, such as persistent litter, marine debris, and potential health risks associated with select plastic types.

Plastic production is growing annually at four percent worldwide (Willet 2007). In 2006, production reached 380 billion pounds, according to Chase Willet of Chemical Market Associates, Inc (Willet 2007). Nearly 25 million shipping containers enter the US by ship, rail, and truck each year; most containers are filled with consumer products wrapped in plastic (United States Senate 2006). High fuel costs and concern about greenhouse gas emissions make plastic packaging more attractive than other heavier materials (e.g., metal, glass, or paper) due to their low weight to volume ratio. Plastics reduce spoilage—and therefore waste—through protection of consumer goods. Moreover, if Western Europe were to continue to consume goods at its current rate, while replacing plastics with alternative materials, it would emit an additional 83.8 kilotons of greenhouse gases annually (Gesellschaft für umfassende Analysen GmbH 2005). Packaging is the dominant market for plastic, and containers and film (thin flexible sheets of plastic such as plastic bags) are the largest plastic packaging markets (American Chemistry Council 2006).

With expanding globalization, increasing consumption, and replacement of other materials by plastic, plastic discards grow. Discarded plastic generally ends up in landfills, although an increasing amount is recycled or incinerated while some, unfortunately, becomes litter. Inaccuracies in reporting have many consumers, and others not directly involved in waste management, believing that landfills are clogged with plastic, but according to the 2006 US Environmental Protection Agency's (EPA) waste characterization study (US Environmental Protection Agency 2006c) most waste is organic material (such as wood, yard trimmings, paper, and food scraps). Plastic takes up 11.9 percent of the United States municipal solid waste stream by weight (United States Environmental Protection Agency 2006c).

Waste management policies primarily emphasize diversion of waste from landfills rather than source reduction, so most of the focus is on recycling heavy items. Unfortunately plastics are a challenging material to recycle. Plastics are lightweight and often voluminous, which presents a challenge in the absence of densification capabilities for efficient collection and handling. Without a significant supply of recyclable material, investment in recycling equipment is difficult to justify.

Most plastic packaging falls within six main types (#1-6), and each type exhibits a wide range of characteristics. For example Polyethylene Terephthalate (PET) #1 bottles differ in material processing characteristics from PET #1 food trays. The variety of resins used in plastics and the low tolerance for contamination among types are some of the reasons plastics have a low recycling rate. Consequently, the best developed reclamation infrastructures for post-consumer plastic materials are for the largest plastic packaging categories: containers (primarily bottles) and film (e.g., bags and pallet wrap) (United States Environmental Protection Agency 2006c).

Bio-based & Biodegradable Plastics

Many consumers find degradability a positive attribute and are attracted to bio-based plastic for its potential degradability. Others are attracted to bio-based plastics because they are produced using a renewable feedstock. Cost and limited performance capabilities, compared to conventional plastics, have restricted the expansion of bio-based plastics (Gruber 2006). However, some bio-based resins recently have become cost-competitive with conventional resins (NatureWorks LLC 2006a). Technological developments, such as nanotechnology, may eventually offer improved performance characteristics but might also introduce potential risks, such as uncertainty about the impact of engineered nano-particles in the environment. One of the great conundrums with bio-based plastic is the desire for the product to be, at the same time, biodegradable, but durable for the product's life.

Definitions

The term *bio-based* refers to plastics produced using carbon that comes from contemporary (non-fossil) biological sources; it may or may not be biodegradable

(Nayaran 2006). The term *biodegradable* plastic is limited to plastics that convert to carbon dioxide, water, and biomass through microbial digestion (Nayaran 2006). They may or may not be bio-based. The American Society for Testing and Materials (ASTM) has standards for bio-based and biodegradability (Nayaran 2006). *Biopolymer* is a term that includes bio-based and some biodegradable plastics, as well as non-plastic material such as proteins, lipids, and DNA. For example, polylactic acid (PLA) is a biopolymer that is also a bio-based and biodegradable plastic (Nayaran 2006).

Development Stages of Bio-based & Biodegradable Plastics

Use of cellulose and starch polymers has grown in packaging applications in recent years. Synthetic biopolymers and polylactic acid (PLA) are currently used in plastic package applications but are in the early stages of commercialization. Companies such Wal-Mart use bio-based plastics in consumer products (Plastic News 2005). Polyhydroxyalkanoates (PHA's) are the newest family of biopolymers to approach commercialization. Through a joint venture between Metabolix and Archer Daniels Midland, production of PHA is slated to be online in 2008 (Metabolix 2006). Like PLA, PHA is produced by fermentation; however, like starch in a plant or lipids in a human, PHA is made inside a living bacterial cell (Shut 2007). According to Metabolix, their materials properties range from rigid thermoplastics to highly flexible plastics. According to Metabolix, "The structural diversity within the PHA family allows the engineering of Metabolix Natural Plastic compositions—sustainably produced—that will be cost-effective, versatile alternatives to over half the synthetic polymers in use today" (Metabolix 2006) (Table 1).

Table 1. Examples of biopolymers and conventional fossil-resource based polymers they could potentially replace (adapted from Gruber 2006, Cornell 2006).

Development Stage	Biopolymers	Producers & Products	Conventional Polymers Biopolymers Could Replace
Commercial	Cellulose	Innovia's NatureFlex	• Polypropylene (PP #5), • Polyethylene Terephthalate (PET#1)
Commercial	Starch Blends	Novamont's Mater Bi	• Polystyrene (PS#6)
Early Commercial	Synthetic Biopolymers	BASF's Ecoflex	• High Density Polyethylene (HDPE#2), • (Linear) Low Density Polyethylene (LLDPE & LDPE #4)
Early Commercial	PLA (Polylactic Acid)	NatureWorks	• Polyvinyl Chloride (PVC #3) • PET, PS, PP, HDPE & LDPE
Pilot	PHA (Polyhydroxyalkanoates)	Metabolix	• PP, PS, HDPE & LDPE

Presently, combined bio-based and biodegradable plastics capture less than one percent of the global plastic market share (European Bioplastics 2007). Considering current capacity for some of the largest US bio-based resin producers (e.g., NatureWorks working towards 300 million pounds) and compared to the nearly 115 billion pounds of plastic produced in the US each year, bio-based plastics face a steep growth curve in order to achieve significant market share (American Chemistry Council 2006).

Most bio-based plastic produced in the US is made from corn, although companies such as Innovia make plastic film from trees (NatureWorks LLC 2006a, Innovia 2007). Eastman Chemical has made cellulose acetate plastic from trees and cotton for over 60 years (Cornell 2006). There are other crops that promise higher feedstock yield per acre, but corn—still abundant and the top US crop—remains the preferred feedstock at this time (United States Department of Agriculture 2007). Each acre produces about 4,099 pounds of resin (NatureWorks LLC 2006b).[1] Therefore, we would need the landmass equivalent of about two or three mid-sized U.S. states (145,000 square miles) to grow enough corn to produce all the resin we consume worldwide.

There has been a surplus of corn in the US, but demand for corn will undoubtedly increase as world population grows. Most beef cattle eat corn-based feed, so rising beef consumption also impacts corn supply (Iowa Corn 2007). Another large source of demand is ethanol produced from corn. The development and use of crops for fuel, feed, and feedstock for materials will be impacted significantly by government policies, including subsidies, incentives, and/or exemptions. The uncertainty of what form these policies will take—and by extension, how they will influence the marketplace—makes it difficult to project the likely growth trajectory of bio-based plastics.

Life Cycle Issues

Beyond production limitations, we must also consider the impact of conventional agricultural practices on the environment, including water consumption and contamination, soil erosion, and greenhouse gas emissions. Corn production, for example, requires fossil resources for fuel, fertilizer, and pesticides.

Many lifecycle analyses for plastics, including bio-based, are limited to analyzing the impact up to the point of resin pellet production. These studies do not take into account other factors, such as product performance as it relates to feedstock material efficiency. An important element in comparing materials is the environmental impact per unit of weight versus environmental impact per unit of use so that comparisons are made for

[1] One acre produces about 183 bushels of corn, and since each bushel produces about 56 pounds of corn, one acre produces about 10,248 pounds of corn (Iowa Corn). According to NatureWorks, they use 2.5 pounds of corn to produce 1 pound of resin (NatureWorks).

equal functional use, such as 1000 gallons of a packaged fluid such as water. Past life cycle analyses (LCA) compared impact, such as greenhouse gas emissions, per material weight, rather than emission per unit of use, but more complete LCA's will consider environmental impact through a product's entire life—not just through manufacture. A material's weight per unit of use, which influences transportation costs, could change a product's environmental impact dramatically. For example, NatureWorks' Polylactic Acid may reduce greenhouse gas emissions during production but create more CO_2 in the transport of products if the application requires more resin to ensure product protection under pressure or under variations in temperature.

End of Life Issues

End-of-life scenarios for plastics have also not been addressed in many life cycle analyses. If a material is composted or recycled, how does this affect the product's total greenhouse gas emissions? It is critical that we consider the complete life cycle from production of feedstock through a product's end of life. For bio-based plastic, the only environmentally positive end-of-life option at this time is composting, since bio-based plastic lacks a recycling infrastructure. Unfortunately composting is not a simple solution, and composting and degrading are not interchangeable.

The general public finds degradability a positive attribute and is attracted to bio-based plastic for its potential degradability, but it is important that we understand the various ways a material degrades and the subsequent impacts. Degradation of bio-based plastics often requires very specific conditions (California Integrated Waste Management Board 2007). Many bio-based plastics in the market only degrade at the high temperatures found in commercial food waste compost facilities (California Integrated Waste Management

Board 2007). Landfills are built to prevent degradation, but most fail eventually. When material degrades in the absence of oxygen, as it does in a landfill, it produces methane, a potent greenhouse gas (United States Environmental Protection Agency 2006b). Because of the specific conditions required for degradation, many bio-based plastics that become litter will persist in the terrestrial and marine environment.

In addition to limited end-of-life solutions, bio-based plastics threaten existing recycling infrastructures because manufacturers of bio-plastics are looking to enter the film and bottle markets; these two markets represent the biggest opportunity for growth. Conventional film and bottles are also the two post-consumer plastic applications with the best-developed collection systems and recycling infrastructure. The annual recovery of conventional plastic through the established collection and reclamations systems far exceeds the global production of bio-based plastic (United States Environmental Protection Agency 2006c, European Bioplastics 2007).

In particular, PLA bottles represent a threat to the well-developed PET container recycling infrastructure. Because both PLA and PET sink in water (the PET recycling system uses a float/sink tank to separate the PP lids from the PET bottle), the materials are difficult to separate. PLA also melts at a lower temperature than PET and is a contaminant to the PET stream (Cornell 2006). Near infrared (NIR) technology helps some recyclers sort out contaminants such as PVC and potentially PLA, but it is not foolproof and not all facilities can afford the investment (Cornell 2006).

Too little bio-based plastic is produced at this time to warrant economically feasible separation measures at Material Recovery Facilities (MRFs). Commercial compost programs that accept bio-based plastics are growing but are still very limited across the country. Non-biodegradable caps, rings, and labels further complicate the compost option. Therefore, most packaging ends up in landfills, and it is likely that most bio-based packaging will also end up in landfills unless there is a complete overhaul of our resource/waste management system.

Developments in Sustainable Packaging

In the context of sustainability, growing interest in and demand for new information about the potential for bio-based plastics has resulted in a bloom of conferences (e.g., Biodegradable Plastic in Packaging Applications 2006, Bioplastics 2006, and International Degradable Plastics Symposium 2006). The Sustainable Packing Forum was sold out in 2006, with attendees representing leading international consumer product companies from Proctor and Gamble to Aveda.

The United Nations World Commission on Environment and Development defines *sustainabilit*y as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (United Nations 2007). According to Wal-Mart, *sustainability* refers to their "commitment to better long-term business performance through improved social, economic, and environmental practices" (Wal-Mart 2007a). These definitions illustrate the variation in perspectives and values that exist concerning sustainability and, therefore, the challenge in drawing conclusions about what constitutes a sustainable package or product and how bio-based plastics might play a role.

Bio-based plastics are sprouting up in various applications as companies scramble to establish sustainability programs. Since many consumers view biodegradability or material made from familiar things such as corn or trees in a favorable or health-conscious light, companies can improve their image as environmentally conscious by using biodegradable plastics even if the product might possibly have a significant environmental footprint.

Existing Decision Tools for Choosing Environmentally Preferable Packaging

A limited number of decision tools exist for choosing environmentally preferable packaging. In 2006 Wal-Mart, the largest retailer in the world, began developing a packaging scorecard that aids their buyers in their purchasing decisions (Wal-Mart 2006). The scorecard is a web-based system that allows suppliers to input packaging information in order to determine their particular score. In addition to the data from the suppliers, Wal-Mart assigns a weight to each packaging criterion, showing how much each contributes to the overall scores (Table 2).

Table 2. Wal-Mart's weights and criteria for the February 2007 version of their scorecard (Cornell 2006).

Weight	Criteria
15	Greenhouse gas generation
15	Material value
15	Product / Package Ratio
15	Cube Utilization
10	Transportation
10	Recycled Content
10	Recovery Value
5	Renewable energy
5	Innovation

Wal-Mart has initiated a very complex framework affecting business across the globe. Fortunately, Wal-Mart's leadership has invited stakeholders from various interest groups to participate in the development process, and the scorecard is relatively transparent. As new data emerge the scorecard will likely change, which should drive continuous improvement, depending on the influence and make-up of the various stakeholders.

Ultimately, the buyers for Wal-Mart must also consider cost. The environmental scores suppliers earn contribute only partially to the overall purchasing decision.[2]

Groups beyond Wal-Mart have formed to discuss sustainability and, specifically, how bio-based plastics fit in that arena:

- Organizations such as the Sustainable Packaging Coalition provide a venue, the Sustainable Packaging Forum, for industry stakeholders to define sustainability goals and ways to measure such goals. (Wal-Mart unofficially set the agenda for the 2006 Forum with its scorecard.)
- An ad hoc group of not-for-profits gathered in April 2006 for a Biopolymer Strategy Meeting sponsored by the Institute for Agriculture and Trade Policy, Lowell Center for Sustainable Production, and Clean Production Action. The group continues to meet remotely for the purpose of developing environmental guidelines for bio-based plastics. They are still grappling with the environmental trade-offs between bio-plastics and conventional plastics and are interested in objective criteria beyond Wal-Mart's agenda.
- The Biodegradable Products Institute (BPI) has developed a certification system with a logo

  that companies are using if they claim biodegradability, which has helped prevent false claims on end of life prospects for bio-based plastics.

Several decision making tools existed prior to Wal-Mart's score card. The United States Environmental Protection Agency's Recycled Content (ReCon) tool and

[2] This section is included with permission from Wal-Mart executives, Meghan Blake and Amy Zettlemoyer-Lazar.

Environmental Defense's MERGE tool have their place in the decision making process, but there are other effective and accessible methods of decision analysis that function without the need for dedicated software or access to an organization's program (United States Environmental Protection Agency 2006a, Environmental Defense 2005).

One example is Multiattribute Utility Theory (MAUT), which is my primary framework for illustrating the trade-offs in bio-based plastics. I used Excel to expedite calculations, but MAUT may also be used without the convenience of a computer. MAUT is designed to address trade-offs among multiple objectives to achieve an overall objective (Clemen and Reilly 2001). It allows a decision maker to explore two or more alternatives, or choices, and each alternative is described by multiple attributes. Using a simple method like MAUT enables a decision maker to modify data or other inputs with ease and transparency.

Development of Decision Tool

Steps of Multiattribute Utility Theory

Multiattribute Utility Theory (MAUT), a decision method used to address trade-offs among multiple objectives, involves seven steps:

(1) identification of fundamental objective (e.g., top resin choice for bottle application),

(2) identification of sub-objectives (e.g., best performance),

(3) identification of attributes of sub-objectives (e.g., impact strength),

(4) assessment of attributes' scores (also known as utilities, or data that have been normalized),

(5) assessment of attributes' weights (i.e., the relative priority the decision maker places on one sub-objective or attribute over another),

(6) calculation of overall utility (i.e., most favorable choice) using weights and scores, and

(7) analysis of sensitivity (i.e., analysis of how a change in an attribute's value or weight impacts the overall utility).

Each step will be discussed in detail below. Items in Steps 3, 4, and 5 were identified through use of a survey, which will also be discussed in detail below.

Identification of Objectives & Attributes

Identification of an appropriate fundamental objective, or primary goal, is essential in decision analysis. Sub-objectives are goals that contribute to the fundamental objective. In order to measure progress towards the fundamental objective, each sub-objective must have at least one attribute with a clearly defined measurement. Furthermore, in order to measure whether or not an alternative, or an option being considered, is the best choice leading to the fundamental objective, all relevant sub-objectives and attributes must be represented, but not redundantly or in a highly correlated way.

To explore the trade-offs in switching from conventional plastics to a bio-based plastic, I selected top resin choice in the bottle application as the fundamental objective. Since performance and cost are the two most commonly discussed aspects of packaging, with environmental impact becoming a more significant aspect of packaging, I used those three broad categories to organize my attributes. The three categories served as sub-objectives. Industry experts guided my selection of candidate attributes.

To identify the most important packaging attributes within the three broad categories, I surveyed key stakeholders, including people working in the for-profit sector as well as not-for-profit sectors, by sending out a memo and survey instrument through email with a personalized message requesting their assistance in identifying important characteristics for evaluating performance of plastic bottles (Appendix). The survey presented three broad categories with eight to thirteen specific packaging attributes to the key stakeholders with a request that they rate the broad categories and the attributes. A copy of the survey is included on the next pages.

Plastic Packaging Criteria Survey

Section One Instructions

With regard to your view of plastic bottle packaging, please rate each of the three categories below, 1 to 10, with 1 being unimportant and 10 being very important. Please rate these before moving on to the lists below.

____Environmental Impact
____Performance
____Cost

Section Two Instructions

Please add any additional characteristics to the list below. Then rate the characteristics by their order of relative importance, 1 to 10, with 1 being unimportant and 10 being very important. I am most interested in how you rate the characteristics but will also appreciate any comments or suggestions about the units I have selected.

Environmental Impact

Rating	Characteristic	Metric/Units	Comments
	CO2 to make a 20 oz bottle	Lbs CO2E per thousand bottles	
	Fossil Resource Use to make a 20 oz bottle (from earth to bottles)	MJ/thousand bottles	
	Water consumption in production of 20 oz bottle (from earth to bottles)	Gallons/thousand bottles	
	Resin needed to make 20 oz bottle (source reduction and energy savings in transportation)	Lbs/thousand bottles	
	Top Load-strength (affects transportation efficiency and product loss)	PSI	
	Potential for recycled content	Yes or No	
	Recycling Rate	% used bottles recycled	
	Compost Rate	% used bottles composted	
	Complete combustion produces products other than water and CO2	Yes or No	
	Use of plasticizers	Yes or No	

Additional Suggestions or Comments:

Performance

Rating	Characteristic	Metric/Units	Comments
	Shelf life- Water vapor transmission rate	gm-mil/m2/ 24hr-atmosphere	
	Shelf life- Gas barrier	cc-mil/m2/ 24hr-atmosphere	
	Impact Strength	% survival from drop of X feet	
	Top Load-flexural modulus	psi	
	Heat Deflection- glass transition temperature	°C	
	Heat Deflection-maximum storage temperature	°C	
	Heat Deflection-maximum filling temperature	°C	
	Appearance-clarity	% haze	
	Appearance-color	L*,A*,B*	
	Appearance-surface gloss	%	
	Specific gravity	Gms/gm	
	FDA status for food contact regulated?	Yes or No	
	Top load	lbs	

Additional Suggestions or Comments:

Cost

Rating	Characteristic	Metric/Units	Comments
	Melting point	°C	
	Parison or preform molding cycle time	Seconds	
	Resin cost	$/lb	
	Bottle production rate (nominal 20 oz bottle)	lbs/hour/machine	
	Secondary packaging costs	$/thousand bottles	
	Bottle cost	$/thousand bottles	
	Material yield	%	
	Class I bottle yield	%	

Additional Suggestions or Comments:

Thank you!

Respondents from the for-profit sector included directors of packaging or government affairs for brand owners, trade associations, retail companies, and resin manufacturers. The not-for-profit sector consisted of environmental advocacy organizations.

I received 12 responses out of 28 surveys sent for a response rate of 43 percent. Five respondents represented the not-for-profit sector while seven represented the private sector.

The respondents rated the three sub-objectives (performance, environmental impact, and cost) between one and ten, with ten indicating the highest level of importance in contributing to a superior plastic bottle. They also rated a selection of plastic bottle attributes under each of the three broad categories between one and ten. I also requested comments and suggestions concerning the units and attributes, or characteristics, I had pre-selected.

With one exception, those surveyed from the not-for-profit sector only rated the three broad packaging categories and the individual rates within the environmental impact sub-objective group; they did not rate performance or cost attributes, so the rates on the performance and cost attributes are representative of those involved in the manufacture or sale of plastic bottles.

I then omitted attributes that received consistently lower ratings from both survey groups, to produce the objective hierarchy in Figure 1.

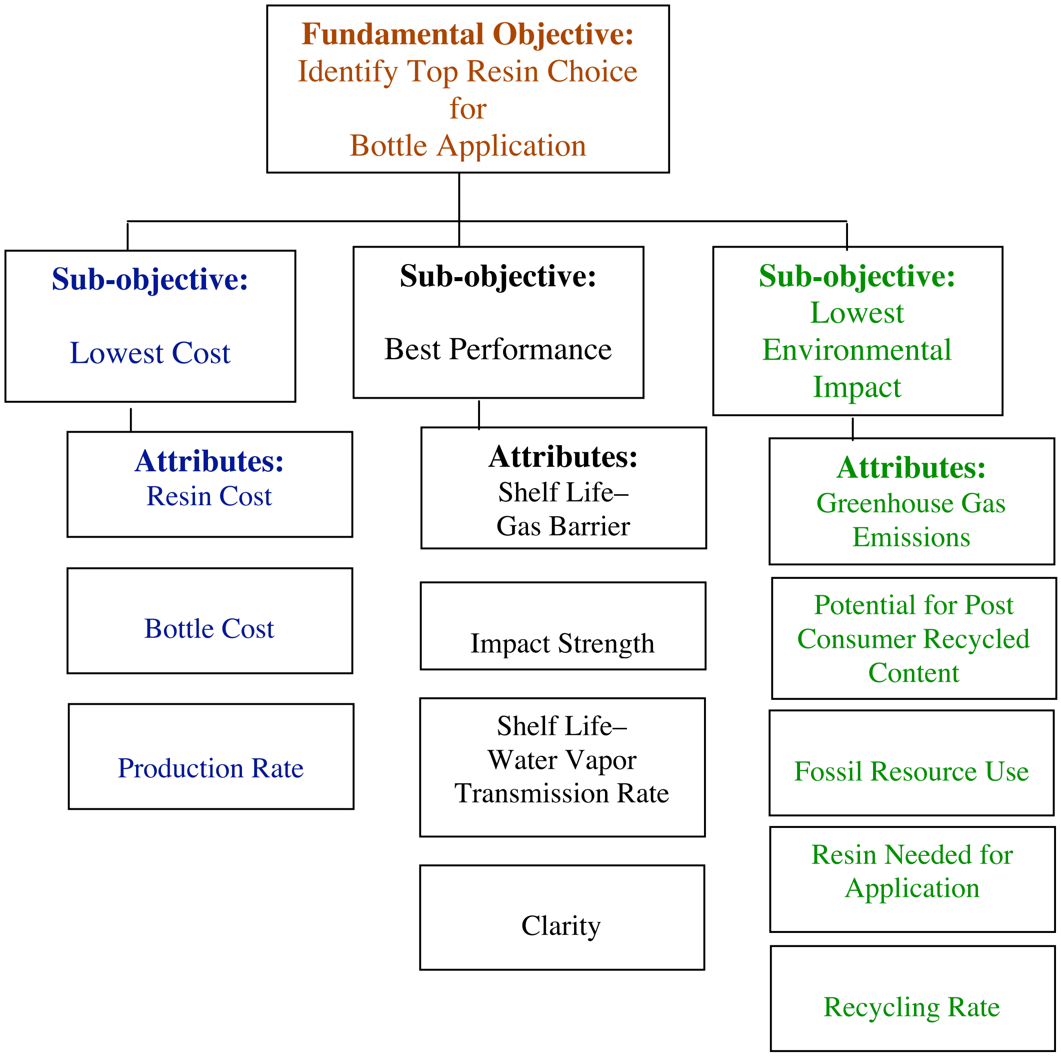

Figure 1. Hierarchy of fundamental objectives, sub-objectives, and their measurable attributes for choosing among plastic bottles. Attributes are packaging criteria that respondents in a survey identified as most important.

From the survey, I gathered a list of additional attributes to consider in future decision analysis for the bottle application including:

- Thermal stability
- Top load strength
- Appearance (color, gloss)
- Ability to use manufacturing plant scrap

- Percent renewable energy
- Compost in place of recycling rate
- Use of potentially toxic additives
- Reusability

Selection of Alternative Plastics to Analyze

Below are the plastic bottle types I selected as alternatives to analyze during the development of the decision tool.

1. Extrusion Blow Molded High Density Polyethylene (HDPE #2),
2. Injection Stretch Blown Polyethylene Terephthalate (PET #1),
3. Injection Stretch Blown Polylactic Acid (PLA #7), and
4. Extrusion Blow Molded Polypropylene (PP # 5).

Many resins are used to make plastic beverage bottles, but I selected the two most commonly used conventional resins (HDPE and PET) as well a third resin (PP) that is picking up market share. PLA is a bio-based plastic resin and the only one currently used in the bottle application.

Collection of Bottle Data

Bottle data for the attributes was difficult to gather since companies prefer not to make bottle information available to competitors. Also, efforts are underway through various organizations to develop up-to-date life cycle analyses, but these data are not yet available. I used the best available data gathered through conversations with industry experts. The goal was to build a framework for ongoing analysis, so I expect the data to change and the data inputs to be updated for future analysis.

Scores & Weights

There are various methods used to "normalize" data measured in disparate scales (e.g., monetary or weight) to a common scale. Once data are normalized, each value is referred to as a "score" (U) (Clemen and Reilly 2001). For this analysis, I used "proportional scoring," which assumes a linear relationship between an attribute score and the relative satisfaction of the decision maker with that score, compared to the best and worst scores for the alternatives being considered (Clemen and Reilly 2001).

In order to determine the relative score for a given attribute, the absolute score is compared to the best and worst scores among the alternatives. For example, HDPE's relative greenhouse gas emission score is determined by U=(2.1-2.3)/1.2-2.3) = 0.18, where 2.1 is HDPE's absolute greenhouse gas emissions in arbitrary units, 2.3 is the worst among the four alternatives, and 1.2 is the best. On a scale of zero to one, HDPE thus has a score of 0.18, which will be used during the evaluation of alternative plastics. The alternative with the best value will have a score of 1 and the alternative with the worst value will have a score of 0.

After determination of the scores, MAUT assesses the relative priority the decision maker places on one sub-objective over another and on one attribute over another. This value is often referred to as the "weight." The weight given to an attribute reflects the willingness to trade off one attribute for another to achieve the fundamental objective (Clemen and Reilly 2001).

In order to determine weights for each sub-objective and attribute for the survey respondents, I divided each respondent's rating for a sub-objective (e.g., performance) by the sum of all of that respondent's rates in the category, so that the weights sum to one.

To summarize respondents' preferences, I averaged all the weights for nonprofits and then I averaged the weights for the industry respondents. After observing that both groups produced results within a point of one another collectively, I averaged the weights from both groups, yielding one weight for each sub-objective and each attribute. Both groups rated environmental impact highest, then performance, and cost last, although the environmental nonprofit organization respondents put a slightly greater weight on environmental impact, compared to a slightly greater weight on cost for industry respondents, which is illustrated in Table 3.

Table 3. Survey results including the high, low, and average weights on attributes for the two survey groups, nonprofits and industry respondents.

	Nonprofit Average	High	Low	Industry Average	High	Low
Environmental Impact	**0.44**	**0.70**	**0.30**	**0.34**	**0.40**	**0.30**
Greenhouse Gas Emissions	0.22	0.30	0.20	0.20	0.30	0.10
Recycled Content	0.22	0.30	0.20	0.18	0.20	0.10
Fossil Resource Use	0.19	0.20	0.10	0.20	0.20	0.10
Resin Needed For Application	0.16	0.20	0.10	0.23	0.30	0.20
Recycling Rate	0.21	0.30	0.20	0.18	0.20	0.10
Performance	**0.30**	**0.40**	**0.20**	**0.33**	**0.40**	**0.30**
Shelf life- Gas barrier	N/A	N/A	N/A	0.25	0.30	0.20
Impact Strength	N/A	N/A	N/A	0.25	0.30	0.20
Shelf life-Water vapor transmission rate	N/A	N/A	N/A	0.26	0.30	0.20
Clarity	N/A	N/A	N/A	0.24	0.30	0.20
Cost	**0.25**	**0.30**	**0.10**	**0.32**	**0.40**	**0.30**
Resin Cost	N/A	N/A	N/A	0.34	0.40	0.30
Bottle Cost	N/A	N/A	N/A	0.34	0.40	0.30
Production Rate	N/A	N/A	N/A	0.32	0.40	0.30

Evaluation of Alternative Plastics Using Packaging Attributes

With weights and scores defined I created a decision matrix, or tool, in Excel, which presents the four alternatives. I used Excel to develop the decision tool because it is widely available and for future analyses it will allow easy modifications to the weight a decision maker places on each sub-objective and each attribute. The decision matrix in Table 4 illustrates how the weights and scores for each sub-objective and attribute determine which material type is the best choice for use in a plastic bottle.

Table 4. A sample decision analysis tool using multiattribute utility theory to determine the best plastic packaging resin for the bottle application. The four resins include high density polyethylene (HDPE), polyethylene terephthalate (PET), polylactic acid (PLA), and polypropylene (PP).

Characteristic	Weights	Units	Combined WT	HDPE	PET	PLA	PP
Environmental Impact	**0.40**						
Greenhouse Gas Emissions	0.21	tons 100 yr CO_2 equivalent /ton resin [a]		2.10	2.30	1.20	1.80
		Score*		*0.18*	*0.00*	*1.00*	*0.45*
Recycled Content	0.20	potential for post consumer content [b]		no	yes	no	no
		Score*		*0.00*	*1.00*	*0.00*	*0.00*
Fossil Resource Use	0.20	tons FRU/tons material [c]		0.94	0.94	0.86	1.00
		Score*		*0.43*	*0.43*	*1.00*	*0.00*
Resin Needed For Application	0.20	density of resin used for bottles (gm/cm3) [d]		0.97	1.37	1.24	0.93
		Score*		*0.91*	*0.00*	*0.30*	*1.00*
Recycling Rate	0.19	% [e]		0.29	0.23	0.00	0.05
		Scores		*1.00*	*0.80*	*0.00*	*0.17*
		Environmental Utility*		**0.197**	**0.177**	**0.187**	**0.130**

Note: table continues on next page

<u>Performance</u>	**0.30**					
Shelf life- Gas barrier	0.26	cc-ml/m2/24hr-atmosphere[f]	150	10	60	200
		Score*	*0.26*	*1.00*	*0.74*	*0.00*
Impact Strength	0.25	Elmemdorf tear strength[g]	120	2600	64	600
		Score*	*0.02*	*1.00*	*0.00*	*0.21*
Shelf life-Water vapor transmission rate	0.25	gm-ml/m2/24hr-atmosphere[h]	0.50	2.0	23.0	0.7
		Score*	*1.00*	*0.93*	*0.00*	*0.99*
Clarity	0.24	% haze[i]	1	3	3	2
		Score*	*0.00*	*1.00*	*1.00*	*0.50*
		Performance Utility**	**0.097**	**0.295**	**0.130**	**0.126**
<u>Cost</u>	**0.30**					
Resin Cost	0.34	($/lb)[j]	0.59	0.70	0.75	0.69
		Score*	*1.00*	*0.31*	*0.00*	*0.38*
Bottle Cost	0.34	$/1000 bottles[k]	68	62	70	81
		Score*	*0.68*	*1.00*	*0.58*	*0.00*
Production Rate	0.32	lbs/hour / machine[l]	436	1,812	1,700	370
		Score*	*0.05*	*1.00*	*0.92*	*0.00*
		Cost Utility**	**0.18**	**0.23**	**0.15**	**0.04**
Overall Utility**			**0.470**	**0.702**	**0.465**	**0.294**

Legend

* Score refers to preference rating and is also known as "utility"

** The utilities displayed represent the sum, over all attributes, of the product of the weight on each attribute and the score for that attribute for a particular alternative.

Sources

a (Strategic Business Analysis, Ltd. Container Consulting, Inc. 2006)
b (United States Food and Drug Administration 2007)
c (Swiss Agency for the Environment, Forests and Landscape 1998)
d (Wal-Mart 2006c)
e (Association of Post Consumer Plastic Recyclers 2007)
f (TDA Research 2006)
g (Stanleco 2006)
h (TDA Research 2006)
I (Private Communication with Industry Experts 2007)
j (Private Communication with Industry Experts 2007)
k (Private Communication with Industry Experts 2007)
l (Strategic Business Analysis, Ltd. Container Consulting, Inc. 2006)

With new life cycle studies, data on greenhouse gas emissions and fossil resource use will likely change in the near future. Since my overall goal is to help organizations resolve trade-offs between advantages and disadvantages of different materials, I made the tool flexible enough to incorporate not only changes in weights but updates in data. I added a function in Excel to identify best and worst values so that a user can simply insert new data.

Calculating the Overall Utility

To calculate the overall utility (Table 4), I summed, over all attributes, the product of the weight on each attribute and the score for that attribute for a particular alternative. A higher utility indicates a more favorable choice (Clemen and Reilly 2001

The overall utility is determined by

U (Plastic)= (W1*w1)*s1 +(W1*w2)*s2 +(W1*w3)*s3+(W1*w4)*s4+ (W1*w5)*s5+ (W2*w6)*s6+…..(W3*w12)*s12

where "W" represents the weight on the sub-objectives, "w" represents the weight on attributes, and "s" represents the scores for each attribute value for each alternative. For example, the calculation for the overall utility of Alternative One, HDPE, would be:

0.47=[(.4*.21)*.18+(.4*.2)*0+(.4*.2)*.43+(.4*.2)*.91+(.4*.19)*1]+[(.3*.26)*.26+(.3*.25)*.02+(.3*.25)*1+(.3*.24)*0]+[.3*.34)*1+(.3*.34)*.68+(.3*.32)*.05]

Discussion of Results

The highest utility was calculated for PET (Figure 2), indicating that it is the most favorable choice given the preferences of those surveyed and the data available. The factors that contributed the most to PET's overall utility were bottle cost, production rate, gas barrier, and recycled content (Figure 2). PET is currently the most commonly used resin in the beverage bottle application, which is congruent with my results (Association of Post-Consumer Plastic Recyclers 2007).

PLA and HDPE offer nearly the same overall utility but HDPE has the highest environmental utility. PLA has a higher performance utility than HDPE, which enables it to compete with PLA in its overall utility. PP has the lowest overall utility.

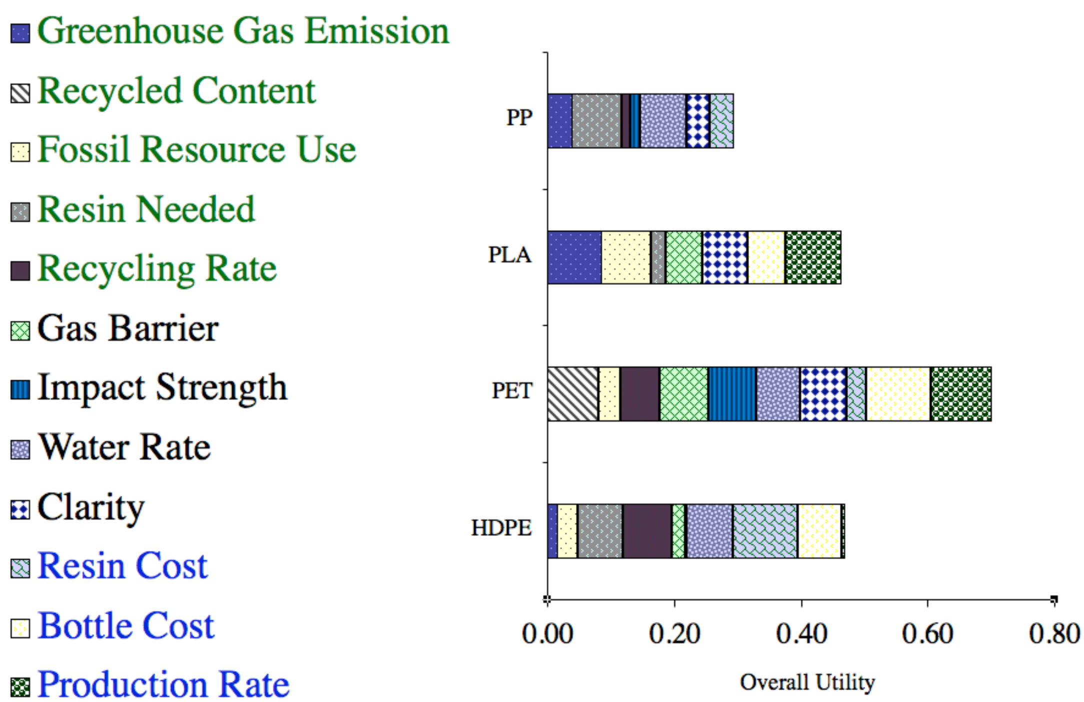

Figure 2. Overall utility for four bottle resin alternatives including polypropylene (PP), polylactic acid (PLA), polyethylene terephthalate (PET), and high density polyethylene (HDPE). Different sections of the bar graph represent how much each attribute contributed to overall utility.

Sensitivity Analysis

Sensitivity analysis allows the decision maker to explore how much change in an attribute value or weight within the model must occur for the overall ranking of alternatives to change (Clemen and Reilly 2001). I used the existing matrix to test every weight and every value to determine which single input could change the overall utility enough to displace PET as the best choice.

No single attribute change can be improved enough to make PLA displace PET as the top choice. Even if all the environmental and all the cost attributes increase to their maximum levels, PLA still does not surpass PET in overall utility. Only with major changes in three of the performance attributes does PLA achieve the top rank:

In order for PLA to achieve the highest overall utility the following levels of change must occur:

Gas Barrier—83% improvement

Impact Strength—3963% improvement

Water Vapor Transmission—91% decrease

Two of the values must improve to the level of PET's performance and one must improve to the level of HDPE's performance, which is highlighted with a box in Table 5.

Table 5. Demonstration of how changes in three performance values can change the overall utilities for the four alternatives including high density polyethylene (HDPE), polyethylene terephthalate (PET), polylactic acid (PLA), and polypropylene (PP).

Characteristic	Weights	Units	HDPE	PET	PLA	PLA ***	PP
Performance	**0.30**						
Shelf life- Gas barrier	0.26	cc-ml/m2/24hr-atmosphere[a]	150	10	10	**60**	200
		Score*	*0.26*	*1.00*	*1.00*		*0.00*
Impact Strength	0.25	Elmemdorf tear strength[b]	120	2600	2600	**64**	600
		Score*	*0.02*	*1.00*	*1.00*		*0.21*
Shelf life-Water vapor transmission rate	0.25	gm-ml/m2/24hr-atmosphere[c]	0.50	2.0	0.5	**23.0**	0.7
		Score*	*1.00*	*0.00*	*1.00*		*0.87*
Clarity	0.24	% haze[d]	1	3	3		2
		Score*	*0.00*	*1.00*	*1.00*		*0.50*
		Performance Utility**	**0.097**	**0.225**	**0.300**		**0.117**
Overall Utility**			**0.470**	**0.633**	**0.635**		**0.285**

Legend

* Score refers to preference rating and is also known as "utility"
** The utilities displayed represent the sum, over all attributes, of the product of the weight on each attribute and the score for that attribute for a particular alternative.
*** PLA's actual attribute values

Sources

a (TDA Research 2006)
b (Stanleco 2007)
c (TDA Research 2007)
d (Private Communication with Industry Experts 2007)

Next I modified each of the weights on environmental impact attributes to show how a decision maker's set of preferences can alter the outcome, which is illustrated in Table 6. Finally I modified just the weights on the sub-objectives (Environmental Impact, Performance, and Cost) to show how a decision maker's set of preferences can alter the outcome, which is illustrated in Table 7.

Table 6. Demonstration of the change in overall utilities through shifting the weights on environmental attributes for the four alternatives high density polyethylene (HDPE), polyethylene terephthalate (PET), polylactic acid (PLA), and polypropylene (PP).

Variations in Weights on Environmental Impact Attributes						Results on Overall Utilities			
Greenhouse Gas Emissions	Recycled Content	Fossil Resource Use	Resin Needed For Application	Recycling Rate		HDPE	PET	PLA	PP
21%*	20%*	20%*	20%*	19%*	→	0.470	**0.702**	0.465	0.294
70%	7.5%	7.5%	7.5%	7.5%	→	0.394	0.593	**0.598**	0.327
0%	100%	0%	0%	0%	→	0.273	**0.926**	0.279	0.164
0%	0%	100%	0%	0%	→	0.444	**0.697**	0.679	0.164
0%	0%	0%	100%	0%	→	**0.636**	0.526	0.397	0.564
0%	0%	0%	0%	100%	→	0.470	**0.702**	0.465	0.294

* Originally estimated weights   Note: Bold indicates highest scoring alternative

Table 7. Demonstration of the changes in overall utility through shifting weights for the three sub-objectives for the four alternatives including high density polyethylene (HDPE), polyethylene terephthalate (PET), polylactic acid (PLA), and polypropylene (PP).

Weights on Sub-objectives				Impact on Overall Utility			
Environmental Impact	Performance	Cost		HDPE	PET	PLA	PP
40%*	30%*	30%*	→	0.470	**0.702**	0.465	0.294
100%	0%	0%	→	**0.496**	0.468	**0.469**	0.328
0%	100%	0%	→	0.323	**0.983**	0.435	0.421
0%	0%	100%	→	0.586	**0.769**	0.494	0.126

* Originally estimated weights   Note: Bold indicates highest scoring alternative

Only a dramatic shift in weight to greenhouse gas emissions within the environmental impact attributes could push PLA ahead of PET without significant changes in material and bottle technology. PLA surpasses PET but ties with HDPE when all the weight is placed on environmental impact. Tables 6 and 7 also demonstrate that the outcome would be the same whether I used weights contributed by environmental nonprofit respondents only or the industry respondents only since dramatic shifts in weight are required for PLA to achieve the highest overall utility; the two groups, nonprofits and industry, generated similar weights for each of the sub-objectives (Table 3).

Feedback from Users

Most feedback from industry experts who have reviewed the tool has been very positive. Stakeholders appreciate having many of the key elements of the decision clearly defined.

The most critical feedback on the decision tool was that one reviewer felt that the results were totally dependent on the types of polymers I chose to evaluate and that I dictated the outcome by choosing particular polymers. Because I assign a 1.0 score to the best and a 0.0 score for the worst, he said I "skewed" the numbers. He suggested that if I included all resin types my 1.0 and 0.0 would change, thus significantly changing my outcome, with PET no longer receiving the highest overall utility. I actually chose the resins most commonly used in commercial applications, which also happen to have better values for most of the attributes used in my decision tool, so including other resins would not have changed the ranking between the four alternatives in my decision analysis.

Others questioned the values I decided to use for greenhouse gas emissions and fossil resource use. I used the best available life cycle inventory data, but the studies I used have been criticized for not providing analysis beyond the point of pellet production.

Another general critique was the impact weight had on demonstrating overall utility. Weight is a subjective expression of relative importance of attributes to the overall utility and therefore the reviewer questioned its use in the decision making process.

Discussion of Further Development of Tool

The version presented here provides a framework, but I plan to update the tool and the information used in the tool as new information becomes available and priorities change. The most important modification I plan to make is an update of values when new life cycle inventory data become available. Attributes in the performance sub-objective may also represent environmental impact attributes as we better define the relationship between performance failure, waste, and environmental impact. For example, a package that fails to withstand impact during shipment creates waste, which is costly—both environmentally and economically. Using more resin to achieve strength or barrier requirements results in a heavier product, which results in more fossil resource use.

In addition to combining some attributes, I may incorporate additional attributes that I obtained during the survey process. For example, I might incorporate percent of renewable feedstock as an attribute or add compost rate to the recycling rate attribute. Several representatives from the environmental community requested that I incorporate attributes for use of potentially toxic additives and for reusability. In hindsight I should have omitted the resin cost attribute by incorporating it into the bottle cost attribute.

Ideally the decision maker knows the scores and alternatives before determining weights, but for the sake of capturing the views of a wide audience, I simplified the process of eliciting weights, instead of using a structured method such as "swing weighting" (Clemen and Reilly 2001). The weight a decision maker places on each attribute is very subjective and depends on how one alternative relates to the next. Given that my surveyed audience did not have access to actual data or values for the attributes, their weights may not accurately reflect their preferences. In the future, I will run several scenarios to test other scoring methods that reflect nonlinear relationships between performance level and user satisfaction.

Since preferences may well differ among users, I will use my decision tool to capture those differences and demonstrate the impact those differences have on the choice of plastic.

Recommendations

The debate about whether or not to endorse use of a bio-based resin such as PLA in the bottle application has hinged primarily on performance (i.e., the capability to hold water while sitting on a store shelf for a specified time) and its potential disruption of the current recycling infrastructure. My goal has been to elevate the discussion so that we make decisions based on an overall objective and clearly define the trade-offs we are willing to make to achieve that overall objective. If the technology develops to enable a PLA bottle to perform with top scores, will we see lower scores in environmental impact attributes? For example, a bottle manufacturer may need to make a thicker bottle to increase impact strength, which will result in lower environmental performances due to increased resin and fossil resource use.

Provided we see the technical development of bio-based plastics with costs and performance comparable to conventional plastics, the need will grow for more robust approaches to weighing environmental trade-offs. Furthermore, by defining objectives clearly, perhaps we can focus the discussion on achieving specific goals, such as reduction of greenhouse gas emissions, rather than make endorsements for products because we assume them to be “green”, or environmentally preferable.

Acknowledgements

I would like to extend my sincere gratitude to my advisor, Dr. Lynn Maguire, Nicholas School of the Environment and Earth Sciences, Duke University. I will always appreciate her instruction on decision analysis and her patient guidance. I would also like to acknowledge my colleagues, David Cornell, Judith Dunbar, Patricia Moore, Dr. Ann Motten, Chase Willet, and to all survey respondents.

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<u>Appendix</u>

December 15, 2006

Ladies and Gentlemen:

I am seeking your input for my Masters Project—Masters of Environmental Management Degree—at Duke University. My goal is to construct an effective decision analysis tool to illustrate trade offs associated with choosing different plastic resins for bottle applications. I am surveying many organizations (e.g., not-for-profit, brand owners, etc.) in an attempt to identify the most important criteria in selecting preferred plastic packaging according to a broad range of perspectives.

Privacy

Your feedback is critical to the construction of a practical decision analysis tool. My advisor, Dr. Lynn Maguire, Director of Professional Studies at Duke University, and I will be the only people to view your response. I will aggregate the responses to form the decision tool, therefore no company-specific data will be revealed. By participating in this survey you agree to allow your responses to be used in aggregate form only in "Nina Bellucci's Masters Project" and in public presentations based on that project.

Reward for Participation

In return for participating in this survey, I will provide you an electronic copy of my constructed tool. While the tool will be based on the findings of this survey and hypothetical data, you will be able to alter the inputs to suit your own requirements.

If you choose, I will acknowledge you in my final report.

Timeline

I would appreciate your survey response as early as possible. Please fill in this Word document and return to me by email at Nina.Bellucci@Duke.edu. If you prefer a verbal response please let me know a good time and number to reach you.

Thank you kindly for your assistance,

Nina Bellucci