A TOOL FOR EVALUATING ENVIRONMENTAL SUSTAINABILITY OF PLASTIC WASTE REDUCTION INNOVATIONS

By:

Connie Chow
Dengfeng Qin
Ruimin Yang

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Faculty Advisors:
Greg Keoleian, Professor
Martin Heller, Research Specialist
Michael H. Mazor, Research Specialist

M | SEAS SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY
UNIVERSITY OF MICHIGAN

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Abstract

Plastics and their byproducts are littering our cities, oceans, and waterways, and contributing to health problems in humans and animals. Since plastics have become significant in our economic and social activities, it is urgent and essential to make progress in plastic waste reduction. Many large investors are looking into technologies and solutions that reduce plastic waste, but a sole plastic waste reduction innovation or project does not guarantee or equate to sustainability performance. In this Master's project, the team at the School of Environment and Sustainability (SEAS) investigated the plastics industry, with the objective of developing a framework and sustainability assessment tool for evaluating plastic reduction innovations to support investment decisions.

The team reviewed sustainability assessment literature and studied plastic waste reduction strategies to determine key criteria and a process for evaluating sustainability performance of plastic waste reduction innovations. Through this work, the Plastic Waste Reduction Innovation Sustainability Evaluation Tool (PRISET) was created, setting educational guidelines around the criteria for both investors and other potential users. General guidance is presented for evaluating environmental sustainability of basic business models that focuses on the company's mission & vision, circular economy attributes, and potential scale of the waste reduction innovation. More in-depth tools for evaluating specific technology innovations include third party certifications and life cycle assessments that require expertise to conduct. Waste reduction innovations were classified into four categories: reuse & refill, alternative materials, innovative design and recycling; and specific guidance criteria in the form of questions were presented to highlight key drivers of sustainability performance in each category. Finally, we also conducted a case study to test the feasibility of the tool. Those innovations that address a wider set of criteria are expected to be more preferrable, while feedback from the assessment will also be useful for innovation companies themselves to focus efforts on those criteria they have not addressed.

Acknowledgements

This project could not have been possible without the contributions of various stakeholders. First, we wish to thank our advisors, Dr. Gregory A. Keoleian, Dr. Michael H. Mazor, and Dr. Martin C. Heller, our Masters project client at Morgan Stanley including Jacqueline Lewandowski and Courtney Thompson, and Ellie Moss at Encourage Capital for their regular meetings with our team and their guidance throughout the project. We would also like to show our gratitude for the support from the University of Michigan, especially the School for Environment and Sustainability as well as the Center for Sustainable Systems.

This Masters project was undertaken as part of Morgan Stanley Plastic Waste Reduction Research and Fellowship program between the Center for Sustainable Systems and Morgan Stanley. Our faculty advisors Greg Keoleian, Marty Heller, and Mike Mazor began their research through this program in 2019 with the first output: "Plastics in the US: Toward a Material Flow Characterization of Production, Markets and End of Life" Environmental Research Letters (2020) 15(9): 1-14. 094034. The second output from this program is a forthcoming Center for Sustainable Systems report that builds upon this Master project. Our student team incorporated significant content developed by our advisors including sections of the report that they coauthored.

1. Introduction

1.1 Background

Plastics have become one of the most important materials in modern society because they have many valued qualities such as strength, durability, light weight, and low cost. For context, the growth of plastics production is estimated to be 2.5 times faster than the growth of the world's GDP (Gross Domestic Product). It is also estimated that total production of plastics will double in 20 years[1]. Many industries rely heavily on plastics for packaging, construction, automotive, and many other uses. Plastics, no matter what type, also pose significant environmental, economic, and social problems when products containing plastic materials are retired.

Generally, there are two types of plastic waste pollution around the world: macro plastics and micro plastics. For macro plastics, it was estimated in 2015 that globally, since the invention of plastics, as shown in Figure 1, "approximately 6,300 million metric tons of plastic waste had been generated, around 9% of which had been recycled, 12% incinerated, and 79% accumulated in landfills or the natural environment"[1]. The low recycling rate and environmental externalities created during incineration, landfilling, and leakage indicate that the current plastic waste requires a more comprehensive efficient solution to address the plastic waste problem.

Many researchers have studied specific innovations tackling plastic waste problems. For example, Zheng et al. reviewed the biodegradable plastic alternatives[5]; Wong et al. reviewed how to use plastic waste as a source of fuel[6]; Al-Salem et al. reviewed the recycling and recovery treatment of plastic solid wastes[7]; and Miandad et al. reviewed chemical recycling with catalytic pyrolysis of plastic waste[8]. Despite the plethora of research surrounding plastic waste, its detriments, and how to reduce its consumption, we still need progress in altering large scale plastic wastes.

Indeed, some studies have also been conducted on the harmful effects of micro plastic waste. For instance, Li et al. indicates that plastics have serious effects on marine ecosystems, for example, toxic ingestion or entanglement harms both marine life and humans when absorbing micro polymers[2]. Verma et al. details the current record of toxic pollutants from plastic waste that causes cancer, neurological damage, and disrupting reproductive respiratory systems[3]. Heidbreder et al. points out social perceptions and behaviors towards plastic problems, where people are reluctant to change their behavior on using plastic packages despite being fully aware of the negative externalities[4]. Given the continued widespread application of plastics in the global economy, new innovations along with investments are urgently needed to address the scale of plastic waste problems.

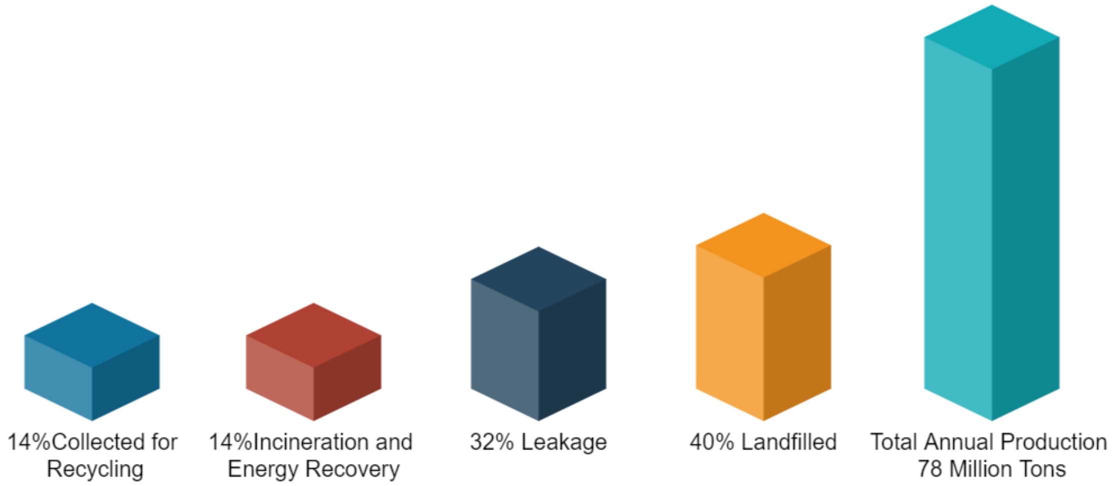

Figure 1. The end-of-life situation of plastic production annually[9].

One resolution for previous stated problems is to introduce more capital into the plastic waste reduction innovations stream, and many investors are doing just that. For example, Morgan Stanley has committed to facilitate the prevention, removal and reduction of 50 million metric tons of plastic waste from entering oceans, landscapes and landfills by 2030 through its own activities and a variety of financial market investments and transactions. Recovering valuable plastic by shifting plastics' linear use to a circular economy can unlock a $706 billion economic opportunity[9]. However, as stated previously, investors now encounter hundreds of possible solutions with various challenges. There are many considerations now at the forefront of these evaluations. For instance, comparing the sustainability of biodegradable plastics versus non-plastic substitutes; quantifying the total energy usage and emission reduction of alternative recycling methods; confirming whether a climate neutral certificate truly represents significant carbon dioxide mitigation. There are many aspects to consider, so it is important to provide guidance and insights to investors in evaluating the sustainability performance of plastic reduction innovations.

1.2 Objectives & Outcomes

The objectives of this project can be divided into three parts: Helping investors and their clients

1) Understand essential indicators of sustainability performance;

2) Characterize and classify plastic waste reduction innovations;

3) Develop a framework and tool to assess the sustainability performance of plastic waste reduction innovations.

The output from this project is the **Plastic Waste Reduction Innovation Sustainability Evaluation Tool**, also referred to as **PRISET**. It can be divided into two parts:

1) General criteria for sustainable business models for companies in either early or growth stages dealing with plastic reduction;

2) Specific criteria of each categorized technology including alternative material, reuse & refill, recycling treatment, and other innovative design.

It is important to note that this tool provides guidance on evaluating innovations by providing important criteria and questions for conducting a sustainability assessment.

2. Tool Development

We conducted our research using a series of literature reviews that informed the design of our tool and its content that includes key criteria and questions for sustainability assessment of plastic reduction innovations. Figure 2 summarizes the methodology we used for developing our evaluation tool.

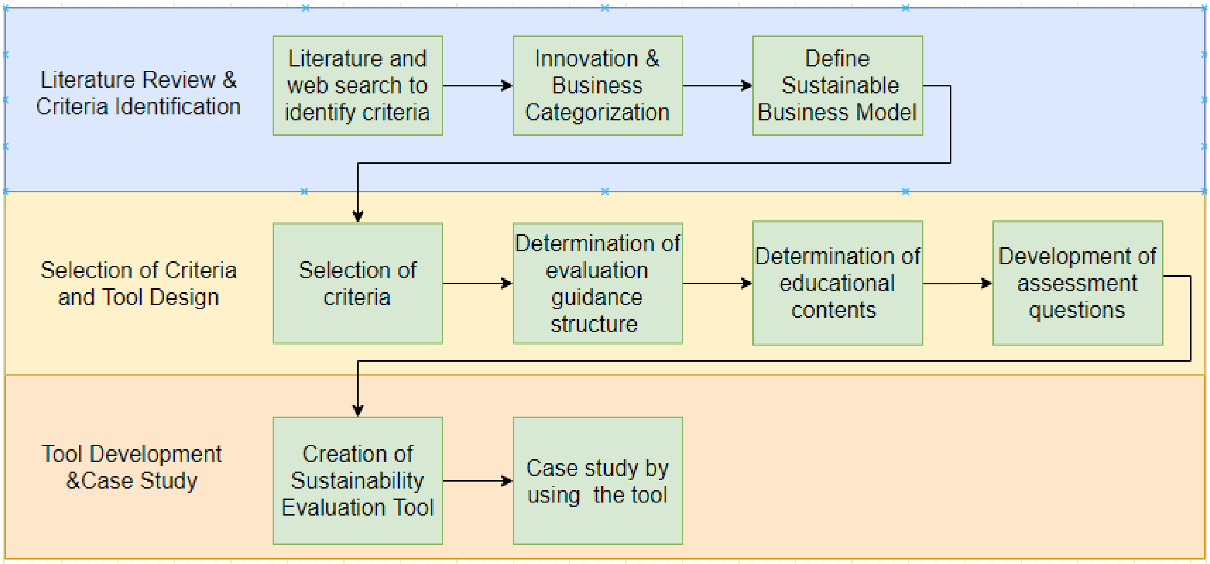

Figure 2. The methodology flow map for developing the evaluation process.

We conducted qualitative analysis to find, assess, and summarize the current plastic sustainability assessment literature, including waste impacts, innovative solutions, plastic business models, and applications and barriers[10]. We selected scientific articles and peer reviewed publications that focused on technologies that reduce plastic waste and how to maintain a sustainable business model. Our tool development process included three stages:

2.1 Initial Information Gathering: We gathered broad background information on the plastic industry, associated environmental impacts, and existing sustainability issues.

2.2 Innovation & Business Categorization: We made categorizations on both businesses and technologies dedicated to reducing plastic.

2.3 Literature Review & Selection of Criteria: We focused on identifying key parameters and metrics for assessing sustainability performance of alternative plastic reduction innovations.

After studying methods for evaluating sustainability performance across waste reduction strategies, types of plastics, and commercialization readiness levels, we developed our framework and process for conducting sustainability assessments. Finally, we tested the tool for feasibility and applicability through a case study. Based on this application of the tool, we also provided practical recommendations.

2.1 Initial Information Gathering

We started gathering information by reviewing reports on plastic waste issues and industry research including those published by the United Nations Environmental Program (UNEP), Citi Bank, the Ellen MacArthur Foundation, and Morgan Stanley. The initial study focused on the basic impacts, opportunities, and constraints in the plastic reduction industry to understand the general landscape of this market.

It is estimated that consumer plastics will impose environmental damages amounting to $140 billion every year, and releasing 390 million metric tons of carbon dioxide [11]. It is estimated that there is a $13 billion impact to marine environments. Marine life is especially vulnerable due to the microscopic particles and toxins entering into the ocean. Plastic manufacturing is energy resource intensive, and municipal solid waste incinerators if not properly operated and controlled can release "toxic gases like Dioxins, Furans, Mercury and Polychlorinated Biphenyls into the atmosphere, posing threats to vegetation, human and animal health and the environment as a whole"[3].

Only a small percentage of plastic has been recycled or reused every year. According to a report from the Morgan Stanley Institute for Sustainable Investing, the plastic industry has a large scale in "packaging, building & construction, automotive, electrical & electronics, household & leisure, agriculture", and in 2015, "only 5% of material value in plastic packaging could be retained for use next year"[12]. The large quantity of potentially recyclable plastic indicates large opportunities ahead in plastic waste reduction.

From our literature review, we identified the following elements to consider in developing our assessment tool (Table 1).

Table 1. The notions we use to make initial information gathering about sustainability aspects of plastic

Technology	Sustianbility Measurment	Business Model
Recylability	Energy Efficiecy	Sustainable Business Model
Reusability	Water Management	Scale of the Plastic Solution
Composting Speed	Land Disturbance	Circular Economy
Composting Condition	Greenhouse Gas Emission	Mission&Vision
Collection Rate	End-of-life Treatment	
	Organic	
	Waste Managment	
	Indirect Impact	
	Pollution Control	
	Standards	
	Certifications	
	Life Cycle Assessment	

The waste hierarchy presented in Figure 3 has been widely used in waste reduction programs and policy. This hierarchy provides a reference for current sustainable plastic management (SPM) -an approach to minimize the environmental damage from plastic waste- and offers guidance for estimating financial opportunities and environmental externalities for each action.

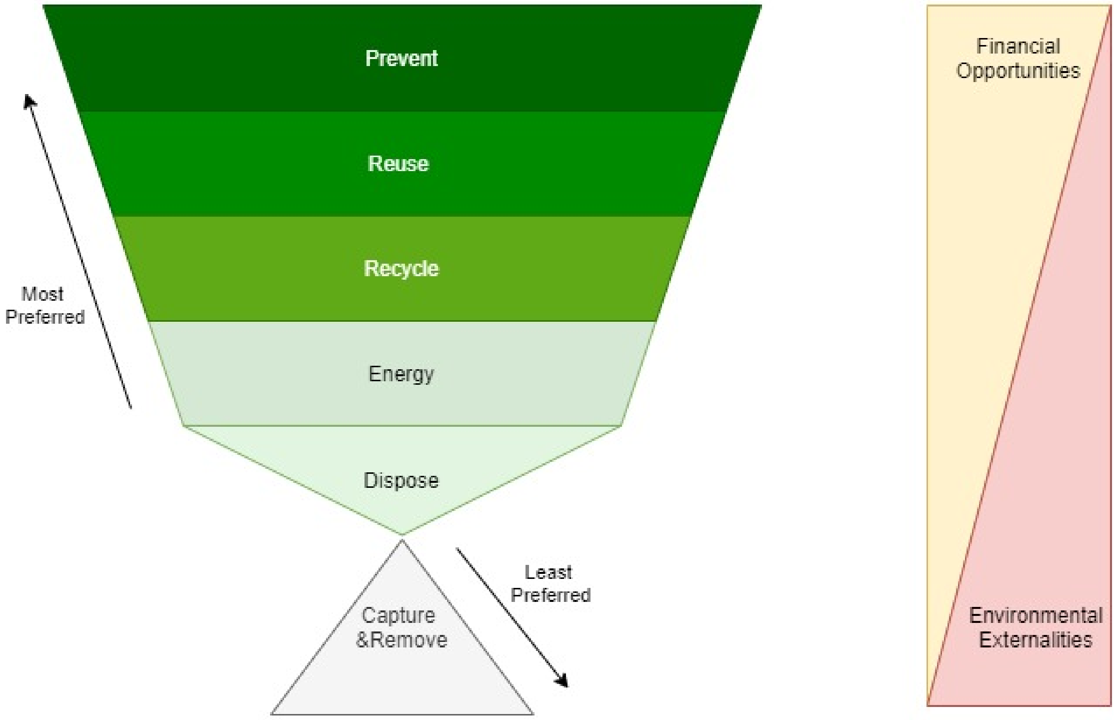

Figure 3. The waste hierarchy of the environmental and financial opportunities within different approaches[10].

2.2 Innovation & Business Categorization

Although each technological innovation has its own opportunities and limitations, we categorized the innovations to provide general guidance for each category. Using a database of over 150 businesses aiming at plastic reduction, we categorized innovations into the following:

- **Source Reductions: This will target reducing the use of plastics.** Methods include reusing and reducing plastic contents. Policies include banning single use plastic bags; Reuse methods include reuse and refill models, repair and refurbish, commercial washing and cleaning or disinfection.

- **Source Substitutions: This will target material substitution** (i.e., replacing the plastic materials). Methods mainly include alternative materials such as non-plastic materials, biodegradable or ephemeral plastics, compostable plastics, edible materials, and other biobased materials.

- **End-of-Life/Material Recovery: This will target efforts to improve separation, recycling, and recovery technologies.** Methods include supply chain design and circular economy design, for example: product-as-a-service and product and packaging redesign; collection, such as distributed collection, sorting (labels, apps, rewards) and tracking (RFID, NFC); mechanical and chemical recycling, such as bottle-to-bottle recycling, plastic to fuel, plastic to energy recovery, repurposing or downcycling, and industrial or community composting.

- **Addressing Collection / Environmental Leakage: This will target preventing leakage or collecting plastic waste.** Methods mainly include last chance capture, such as residential, commercial, or municipal wastewater management, road run-off or storm drain filters, waterway litter catchments, and open ocean capture.

- **Other:** Everything else that falls in this category is visualizations or efforts on raising awareness. Other methods include advanced logistics (backhaul or circular logistics), sharing economy enabling technology and services, and engaging the information and data sector. (technology or platform applications, equipment, financing, big data, etc.)

Table 2a. Innovation categorization

Row Labels	Count of Company
Alternative Material	19
Consumer Products	6
Food & Bev - Container	35
Food & Bev - Packaging	8
Household Products	11
N/A - Not plastic innovation or Not enough information	27
Raising Awareness	4
Ship Packaging	13
Software Platform	5
Waste Management	9
Grand Total	137

Table 2b. Business industry categorization

Row Labels	Count of Company
Addressing Collection / Environmental Leakage	1
EoL/Material Recovery/Recycling	19
EoL/Material Recovery/Recycling; Other	1
N/A - Not plastic innovation or Not enough information	27
Other	6
Source Reduction	37
Source Reduction; EoL/Material Recovery/Recycling	9
Source Substitution	34
Source Substitution; EoL/Material Recovery/Recycling	3
Grand Total	137

We recognize that category level guidance can be useful, but it is not a substitute for in-depth sustainability analysis of individual innovations. For example, restaurants and shipment companies will both prefer reusable products solutions, but their collection or return schemes are different. Therefore, we created another list focusing on categorizing business industries.

From Table 2a and 2b, we found that most companies rely on solutions in source reduction, source substitution, and recycling. This is consistent with the business categorization, since many companies are in the alternative material and container or packaging industries. However, we found a few exceptions. For instance, some food and beverage companies like Cupclub (https://cupclub.com/) and Pulpworks (http://www.pulpworksinc.com/) use a series of methods, including reusable containers, RFID collection, and alternative material designs, to replace their single-use products. There are also firms like MIWA (https://www.miwa.eu/) and TemperPack (https://www.temperpack.com/) targeting non-plastic innovations, such as circular business models and curbside solutions. Although companies are making efforts in designing new alternative and recycling methods, the most common methods are still simple reuse schemes as well as creating educational awareness.

In our research, we focused on the following:

- Understanding the fundamental reasons causing negative environment impacts of the plastic industry and identifying current limitations in creating and implementing solutions.
- Developing methods for evaluating business sustainability models and specific technologies and innovations tackling plastic waste reduction.
- Creating a classification scheme for organizing waste reduction strategies and technologies into a set of categories that will facilitate the assessment of sustainability performance.

2.3 Literature Review & Selection of Criteria

Our team conducted literature review to study and select relevant criteria that would be applicable for our tool. This review focused on academic journals and publications by both government and non-government organizations (NGOs). Through the screening process, we addressed the relationship between life cycle based sustainability performance and plastic waste reduction solutions. Through our analysis of innovations and business models, we determined our final criteria for our tool.

2.3.1 Technologies / Innovations Research

Plastic waste comes from industrial, commercial, and residential sources. To find out how to reduce plastic waste, Ellie Moss, a senior advisor at Encourage Capital has identified four key reasons that drive plastic waste generation[15]:

- Limited Reusability: Many plastic products are not designed to be reusable.
- Challenges with Recycling: Most plastics are not easily recyclable if they are contaminated with other waste such as food. It makes separation of the plastic difficult and more costly.
- Challenge with Composting: Some plastics are compostable, but the availability of municipal composting centers is limited. Additionally, compostability (e.g., how well the material will degrade) is also controversial.
- Contribution to litter: Plastics and even compostable plastics are often discharged into environmental as municipal waste which is not appropriately stored and collected.

There have been many efforts to address these challenges, as shown in Figure 4.

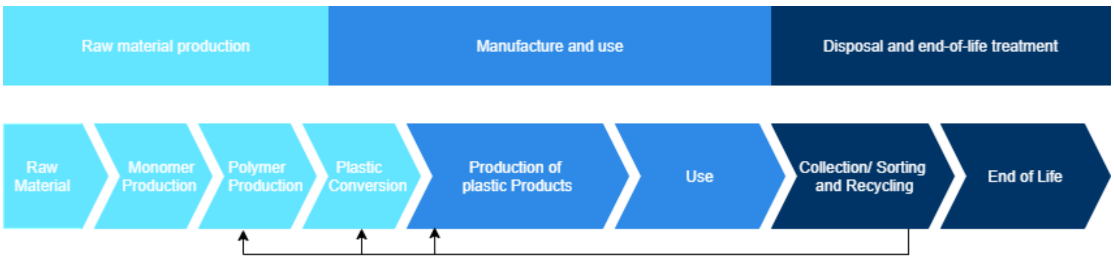

Figure 4. The typical upstream and downstream map of the plastic industry[16].

- In the raw material production stage, some innovations are aimed at producing alternative materials. However, each technology faces its own challenges. Take biodegradable plastics as an example: UNEP indicates that although biodegradable materials can reduce plastic waste, they are expensive to produce, difficult to separate from traditional waste streams, and labeling them as "biodegradable" has caused increasing littering behavior[17].

- In the manufacture and use stages, many firms are encouraging reusable packages or containers, through return incentive or penalty programs. Life cycle assessment is essential in comparing energy, water, emissions and other indicators between single-use and reusable polymers, but Lewis et al. states that broader sustainability analyses are necessary, including "the functionality of alternative bags, their relative cost, convenience for consumers and retailers, and the availability of reuse and recovery systems"[18]. For some coastal areas, single-use paper bags may pose less harmful effects to the marine environment, and reusable containers are really sensitive to real usage rates from consumers. Context in terms of application and consumer behavior are important in evaluating sustainability performance.

- In the disposal and end-of-life treatment stage, businesses focus on resource recovery including materials and energy. There are dozens of different recycling methods, and they share common challenges such as sorting plastic with additives, coating, inks, and other residues; product quality degradation, price fluctuations between virgin and recycled materials, etc[19]. Also, comparison of different recovery methods in sustainability performance can be challenging and controversial. For example, it is difficult to compare chemical recycling that yields valuable petrochemical feedstocks with combustion energy in the form of heat or steam."[7].

- Other innovations focus on more systematic solutions. They provide consumer deposit schemes for increasing recycling rates, push regulations on standardized plastic coating and labels, set charging and pay-as-you-throw methods to incentivize reusing, etc. It can be challenging many cases, to accurately quantify the benefits of such solutions compared to the status quo.

With these studies in mind, we narrowed down the innovation categories into the following:

1) **Alternative Materials**, (similar to source substitution)
2) **Reuse & Refill**, (similar to source reduction)
3) **Recycling**, (similar to End-of-Life / material recovery)
4) **Innovative Design**, (all other innovations)

Each innovation has its own characteristics, indicating different sustainability criteria to evaluate. However, a general business sustainability model analysis is also necessary when evaluating the circular economy or life cycle performance of the innovation, which is shown in Section 2.3.2.

2.3.2 Sustainable Business Model

A sustainable business model is the major premise of a sustainable innovation. Only with a sustainable business model can we discuss and measure the performance of a sustainable product or service. Business systems are complex and can be explained in many ways. To compare different businesses, it is important to have a conceptual framework to codify information[10]. Bocken et al has proposed eight archetypes of sustainable business model[20]:

1) Maximize material and energy efficiency
2) Create value from 'waste'
3) Substitute with renewables and natural processes
4) Deliver functionality rather than ownership, i.e., product-as-a service
5) Adopt a stewardship role
6) Encourage sufficiency
7) Re-purpose the business for society/environment
8) Develop scale-up solutions

These archetypes could address three main problems:

A. Replace linear business or economic model by a circular model
B. Reduce the consumption of natural resources and energy
C. Increase scale of positive impact

In addition, an organizations **mission & vision statements** at a high level can signal an organization's sustainability commitment. In our research, we also identified **Life Cycle Assessment (LCA)** to be the most comprehensive tool to evaluate the environmental performance. It has been standardized through ISO (ISO 14,040/14044)[22]. Given that early-stage products and processes may not be defined enough for rigorous LCA other criteria much be used. **Certification** of key product attributes, although more limited in scope, is another means of validating environmental performance of products.

In short, the final selections of the criteria for general plastic reduction business are:

1) **Mission & Vision**
2) **Circular Economy**
3) **Scale of Plastic Reduction**
4) **Certification**
5) **Life Cycle Assessment**

3. Investment Guidance Tool

3.1 Tool Structure & Use

The guidance for evaluating the sustainability performance of plastic waste reduction innovations is captured in the **Plastic Waste Reduction Innovation Sustainability Evaluation Tool**, also referred to as **PRISET**. This section describes audience assumptions, layout and use.

3.1.1 Tool Structure

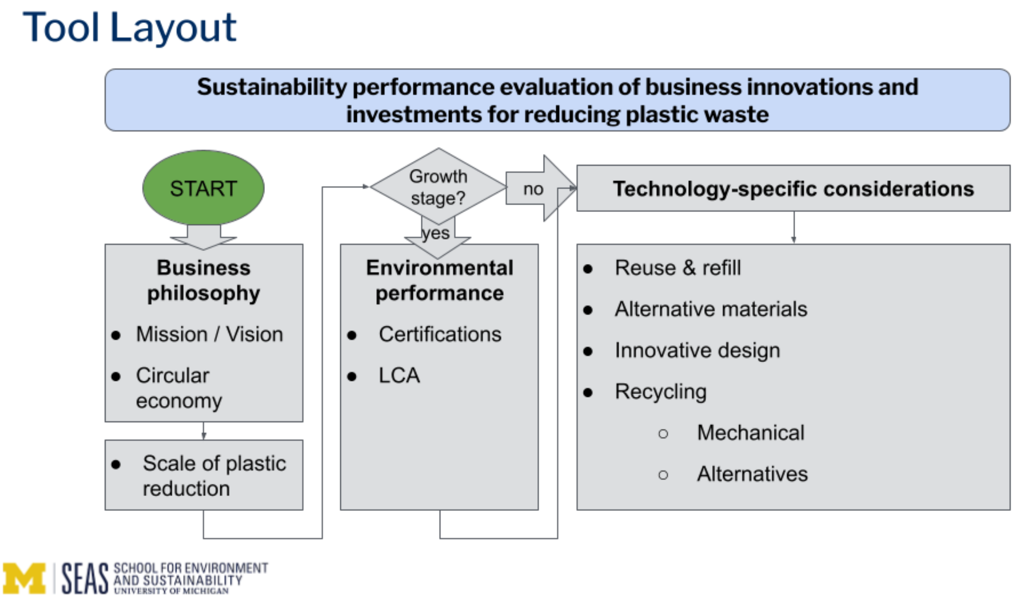

Figure 5. The flow chart mapping of the structure and sequence of PRISET.

PRISET (tool) is based on the assumption that the users understand general concepts of environmental performance. The tool contains criteria to guide the communication with the responsible parties in the business under evaluation. In the document, this entity is referred to the as the focal firm **or business**. The "thing" that the focal firm intends to implement is referred to as the innovation.

Figure 5 shows the mapping of the structure of PRISET. The guidance criteria are organized with consideration to the development stage of the innovation (e.g., technology readiness level) and the type of technology deployed. The mission and the vision of the focal firm initiates the business philosophy portion of the tool and sets the stage for the evaluation. This and a holistic measure of the life cycle impact of the innovation on plastics waste are important for all innovations regardless of development stage. An estimate of the scale of plastics impacted by the innovation is also recommended for all evaluations. A decision is then made based on the technology readiness level of the innovation. Here, if the focal firm is selling into the marketplace (even as a pilot), there should be enough market, production, and sales data to understand the environmental performance and initiate appropriate environmental certifications and a quality life cycle assessment. After these general elements are reviewed, a more targeted discussion specific to the technological details of the plastic reduction innovation is recommended.

Innovations to reduce plastics waste can be found across the plastics value chain. To focus sustainability recommendations on specific areas of concern, the plastics value chain is separated into four overlapping categories: reuse & refill, alternative materials, innovation design, and recycling (See Figure 5). Each category contains sustainability guidance specific to the innovation, the market affected, and often the behaviors impacted. An innovation evaluation may benefit from the guidance criteria of several categories.

3.1.1 Tool Use

Plastics waste reduction is a single attribute within the total environmental impact of any innovation. Directing environmental evaluation toward other metrics is important to ensure holistic environmental performance. The PRISET guided evaluation plays an educational function for the user to understand essential sustainability questions for plastic reduction companies and provide guidance for investors to assist their evaluation on important elements. Additionally, the guidance criteria can be used internally by firms working to reduce plastics waste as part of their environmental management and improvement process.

In many geographies, measuring and reporting broad environmental performance remains largely voluntary. Given this situation, we recommend that the plastic waste reduction potential based on PRISET should be managed as a conversation on the past actions of the focal firm and recommendations on future efforts. If production and sales data are available, the sequential layout of criteria is somewhat arbitrary and we recommend that all guidance criteria appropriate for the innovation be covered before an evaluation is made. When specific guidance is reviewed, there are several scenarios envisioned. If the information exists, the user captures the information and moves to the next criteria. If the information does not exist, the user asks for it to be generated and communicated prior to any final decision on the opportunity. The process starts by reviewing the criteria in the business philosophy portion of the tool. Next evaluate the technology readiness level to determine if there is enough production and sales data to cover the environmental performance sections. For all opportunities, the user should determine which technology category or categories best describes the opportunity. Finally, the technology specific considerations for that category or categories are reviewed.

The output from using the tool is not an absolute metric of a focal firm's ability to sustainability reduce plastic waste. Consider it a tool to gather and organize the relevant environmental information. Judgement is required to incorporate the environmental guidance with other critical metrics used to evaluate potential investments. The January 2018 report from Morgan Stanley Research Embedding Sustainability into Valuation: The Next Chapter recognizes in their Environmental, Social and Governance (ESG) Integration Framework as element 5: "An active judgement call is required. There is no set of rules that can be applied to qualify as ESG integration"[23]. The set of relevant environmental information can be considered as indicators developed from 'observed facts that can reveal relative positions'[24].

3.2 Business Philosophy: Sustainability Aspects of Mission & Vision

3.2.1 Basis / Overview

Understanding the mission and vision of a company can inform us of their purpose, goals, and values. The January 2018 report from Morgan Stanley Research describes internal and external research connecting corporate sustainability efforts and positive financial performance. Governance is identified as a key factor in evaluating environmental and other sustainability achievements[23]. These include corporate governance, ethics and culture. The mission and vision statements should describe what the company is doing and what it intends to achieve. While evaluating innovations focusing on plastic waste reduction, keep in mind the following to ensure alignment across goals and expected outcomes:

- The mission and vision of the company or sub-unit developing the innovation aligns with clients' overarching goal to reduce plastic waste. Conversely, investing in firms or innovations that increase plastic waste - even if unintended - could be a reputational risk.
- Confirm that the Mission - which indicates purpose - contributes to advancing sustainability. Morgan Stanley's research supports the positive relationship between financial and sustainability outcomes. For an innovation to have impact in reducing plastic waste, it must be a success, both technologically and financially.
- The sustainability and social responsibility goals are well-defined and measurable.

3.2.2 Guidance Criteria

- **Does the focal firm's mission and vision support significant prevention, reduction or removal of plastic waste from entering the environment?**
  Companies seeking investment should provide clear claims on their plastic waste reduction goals and approaches. The relationship between their goal and approaches needs to be clear. The evaluation guided by PRISET will support or possibly refute a stated mission and vision, but one should be present.

- **Does the mission convey a purpose that contributes to advancing sustainability?**
  Though the main target is to reduce plastic waste, it will not be effective if the supply chain and business model is not sustainable. Besides providing good products, good services, and reducing waste, the company must demonstrate corporate citizenship -- beneficial for employees, customers, the environment, our communities, and society[25]. It should consider the triple bottom line: people, planet and profits. The use of life cycle thinking for holistic decision making sends the right message.

- **Are sustainability and social responsibility goals well-defined and**

measurable?
A good sustainability and social responsibility goals need to be well defined and measurable. The sustainability goal needs to clarify how success of the focal firm can maximize long-term economic, social and environmental benefits.

3.3 Business Philosophy: Circular Economy Approaches

3.3.1 Basis / Overview

Circular Economy (CE) can be defined as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations[26]. For more information, please refer to Box 1.

While CE is, in part, a paradigm for reducing waste, it is important to note that having circular attributes does not necessarily equate to enhanced sustainability performance[27]. Today, CE strategies are identified within a product or service, and evaluated on how it demonstrates or contributes to waste reduction. Currently, however, metrics to evaluate CE are being developed in the field, though they have not been standardized.

At the high level, the innovation should be self-consistent within the key parameters for reducing plastics waste. For this evaluation tool, we are considering reducing plastic waste as an element in the circular economy while not reducing plastic waste as an element of the linear economy of plastics. Does the innovation, its supply chain, and end of life disposition demonstrate or employ a reduction in plastics (over the incumbent) or a reuse characteristic? It is important that the end of life of the innovation includes recycling into a valuable material stream. Here, being recyclable is not the same as being recycled at the end of life.

Although developed for plastic packaging, the six characteristics defined by the Ellen MacArthur Foundation[28] can be used to guide circular economy thinking more broadly.

1. **Elimination of unnecessary plastic packaging through redesign, innovation, and new delivery models is a priority.**

In general, can decisions made early in the development process reduce the use of plastics when compared to standard actions. Can a single part replace several parts? Can that part be made of plastic with a high recycle value? Can a composite be replaced by a single material? Can a small tweak enable easy disassembly and repair? Can initial design parameters allow the use of recycled resin?

2. **Reuse models are applied where relevant, reducing the need for single-use packaging**.

The end-of-life management of the reusable packaging should be circular: i.e., refurbished for further reuse or recyclable into a valuable recycle stream. Can the reuse cross markets? Can a B-to-B shipping crate be designed to end life as part of a building or civil engineering structure?

3. **All plastic packaging is 100% reusable, recyclable, or compostable.**

Early design decisions can drive the choice of materials. Efforts should be made to use components made from single materials where these materials have value in the recycle market. It should be noted that composability is as much a process as a material. Materials that can compost at low heat (i.e., in a backyard) are a small fraction of "compostable materials" most of which need a high heat industrial composting process.

4. **All plastic packaging is reused, recycled, or composted in practice.**

Point 3 ensures that the materials are recyclable. Point 4 ensures that the reverse supply chain, processing and market realities are demonstrated in practice. Pay attention to the environment or human health impact from the recycling process, e.g., the use of landfill pickers or unregulated deconstructions.

5. **The use of plastics is fully decoupled from the consumption of finite resources.**

The theoretical goal of the circular economy is to decouple economic growth from resource extraction. Consider how the focal firm is moving in this direction. Special attention should be paid to rebound[29]. Where the ultimate impact is to increase the extraction of virgin materials.

6. **All plastic packaging is free of hazardous chemicals, and the health, safety, and rights of all people involved are respected.**

A thorough life cycle assessment needs to be proceeded in order to determine the possible environmental damages and health issues. However, indicators such as toxicity and equity are really uncertain and hard to measure. For more information, please refer to the Life Cycle Assessment section.

3.3.2 Guidance Criteria

CE is a business model though it does not guarantee sustainability, it provides a substitution to the linear supply chain. Among various questions regarding CE, we selected followings as the most important questions to consider:

- **How does the innovation reduce plastic use and/or plastic waste?**
  At the same time, the effect brought by their product or service should be clarified. For example, if a specific method is used to eliminate the plastic waste, how much plastic waste will be reduced per unit, and how is it measured?

- **What is the end-of-life of materials used for the innovation?**
  Considering the end-of-life situation might be the main difference between a linear production system and a circular economy. For example, knowing

whether the innovation requires landfill for waste, releases harmful substances, or needs huge efforts in removing labels and additives to enable recycle, is significant.

- **Does the business plan use holistic, life cycle thinking to consider the up- and down-stream impact on the total quantity of plastics (virgin and recycle) wasted?**
  This should include plastics introduced by the business and any impact the business will have on the plastics marketplace. The holistic measurements could be coupled with the Life Cycle Assessment criteria.

Box 1. Circular Economy

In its most basic sense, the circular economy (CE) stands in contrast to the historically dominant "linear economy," one in which product life cycles typically follow a "take-make-use-dispose" pattern. Yet, the development of the CE concept has occurred over a diversity of disciplinary perspectives, resulting in broad interpretations and differing central tenets. Many have recognized CE as an umbrella concept[30,31,32]that includes lowering material input and minimizing waste generation[33,34] in order to decouple economic growth from natural resource use.[33,35,36] Kirchherr et al. review 114 identified definitions of CE and arrive at the following synthesized definition:

CE is defined as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations"[37].

In many ways, CE represents a "popularization" of concepts and ideas that have been developing along with the field of industrial ecology for multiple decades, and through frameworks such as life cycle assessment, life cycle design, green engineering principles, design for environment principles, and others.

Common strategies of CE include preserving the function of products or services (sharing platforms, Product-Service Systems, multifunctionality); preserving the product itself (durability, reuse, restore, refurbish, remanufacture); preserving product components (reuse, recovery, repurposing of parts); preserving materials (recycling, downcycling); preserving embodied energy (incineration, landfill gas capture)[38].

The Ellen Macarthur Foundation has popularized the "butterfly diagram," as a representation of the CE. The diagram represents many of the "circular" strategies of CE, including preserving the function of products or services (sharing platforms, Product-Service Systems, multifunctionality); preserving the product itself (durability, reuse, restore, refurbish, remanufacture); preserving product components (reuse, recovery, repurposing of parts); preserving materials (recycling, downcycling); and preserving embodied energy-

-(incineration, landfill gas capture). It also captures the importance of CE strategies to incorporate energy sustainability and the transition to renewable energy. Also, Figure 6 illustrates how a linear economy changes to reuse and circular economy by the Netherland Government.

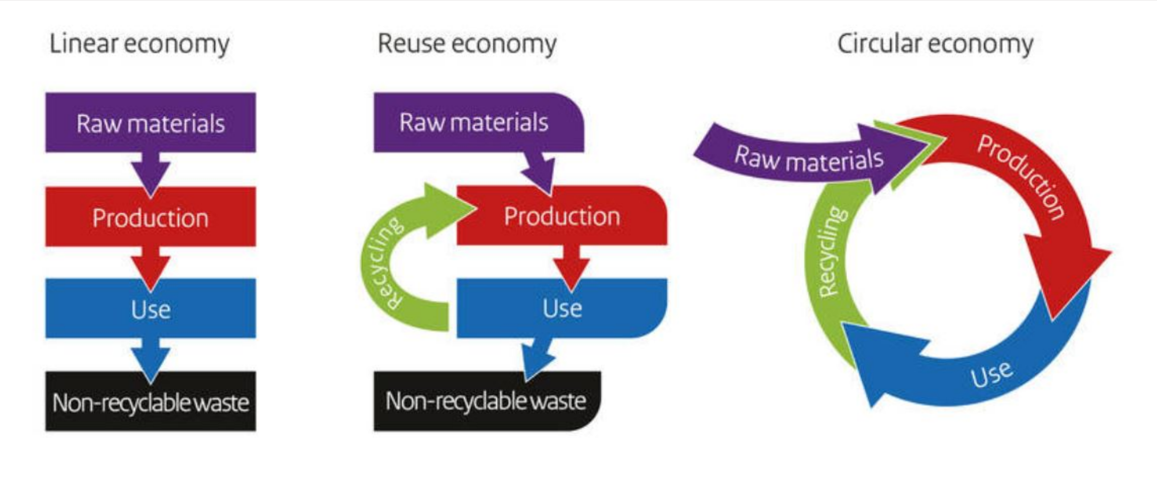

Figure 6. From linear economy to circular econmy[39].

While CE engages a number of critical tenets of sustainability, including decoupling economic growth from natural resource consumption, reducing material inputs, and minimizing waste generation, it is equally important to recognize that CE strategies do not inherently reduce environmental impacts. Dozens of CE metrics have been proposed, ranging in scope and complexity from straightforward recycling rates to combined metrics that integrate mass and time components[40]. These metrics offer valuable means of providing rapid guidance and feedback in planning, design and implementation, but are not sufficient by themselves in assessing sustainability performance, and ultimately require system level assessment through tools such as LCA to assure that CE strategies do indeed result in net reductions in environmental impacts.

3.4 Potential Scale of Plastic Reduction

3.4.1 Basis / Overview

The basis for consideration of "sustainability" or environmental impact often is at the product or material level: how does the performance of product (or innovation) x compare with the status quo? This is critical, but it also is important to consider the extent to which a given innovation will scale within the broader economy. This requires understanding where and how plastics are used currently (see Box 2), what the targeted market for the innovation in consideration is, the amount of plastic used in that market sector, and how the innovation will reduce that plastic use/waste. This potential scalability will influence not only the overall amount of plastic waste that may be reduced, but - if the innovation proves to be environmentally preferable to the status quo - the absolute benefits to sustainability: greenhouse gas emission reductions, reductions in fossil energy use, etc.

3.4.2 Guidance Criteria

The questions regarding scale should focus on both maximum potential and possibility of successful intervention on the reduction of plastic waste.

- **What is the maximum potential for this intervention to reduce plastic use/waste?** (e.g., if the business model were 100% successful)
  The ultimate market success of an innovation/intervention is impossible to predict, but placing some bounds on the potential of a given innovation to reduce plastic use and waste - given current usage in the target sector, the displacement offered by the innovation, and anticipated market penetration - can offer important guidance on its effectiveness as a plastic waste reduction strategy.

- **Does the intervention target a difficult to recycle plastic or product?**
  It also is important to recognize that some plastics, for example, those that are particularly difficult to recycle or do not have a developed recycle market, should be prioritized in reduction / elimination. Therefore, an innovation targeting such a plastic may be important even if its potential to reduce overall plastic mass is lower than another.

- **Does the intervention target a product with a high likelihood of losses to natural environments?**
  Again, interventions targeting the reduction of plastic waste that is more likely to end up as pollution in a natural environment (e.g., plastic shopping bags, convenience food wrappers) may warrant priority, even when the absolute mass of reduction is lower.

3.4.3 Sources of Information

Information on plastic use in specific sectors can be extremely difficult to find, especially at more granular market sector levels. Box 3 offers an example utilizing Economic Input/Output accounts. Market analysis reports may also offer insight. In both of these cases, size/scale is based on economic values, and translating this to physical units (mass) can be challenging.

Box 2. Material Flow of Plastics in the US

Plastics are ubiquitous in today's society, owing to their versatility, light weight, strength, durability, corrosion resistance, thermal and electrical insulating properties, and relatively low cost. Appreciation of the material flow of plastics -- the amount and variety of plastics used in different industrial sectors and how they are disposed at end-of-life -- can greatly assist in identifying opportunities for significant reductions in wasted plastics. The figure below illustrates the flow of plastics through the US economy circa 2017, based on an aggregation of best available data[41]. It offers a sense of scale across polymer types, use sectors and end of life destinations that can provide context and orientation for strategic solutions. Plastic packaging utilizes large quantities of materials in predominantly single-use, 'disposable' applications, clearly warranting focused efforts for reductions where possible and coordinated material recovery and recycling solutions implemented throughout design, recovery and reprocessing. However, the material flow presented here reminds us of an important perspective: over two thirds of the plastics put into use in 2017 found applications outside of packaging. These other use sectors introduce unique challenges as well as opportunities but will also benefit from increased coordination of circular economy thinking between innovation and design and recovery and recycling.

There also are notable gaps in our understanding of the material flow of plastics. Identifying opportunities to improve data access and availability throughout the plastics supply chain will enhance the abilities of innovators and investors to further target plastic waste reduction prospects. Figure 7 shows a flow diagram of production, imports, exports, use, disposal and leakage of plastics in the US in 2017

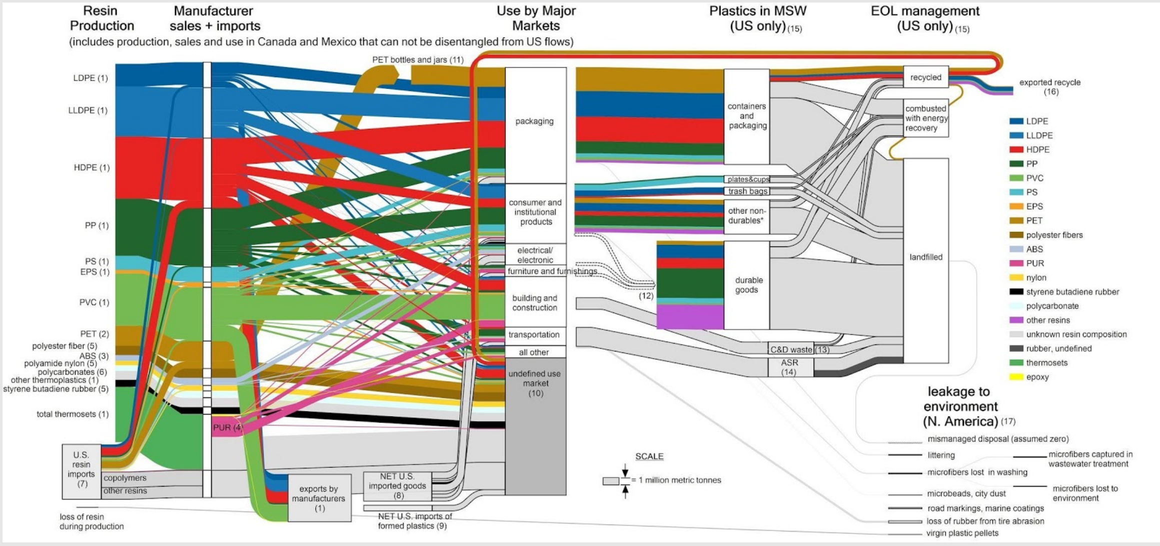

Figure 7. Production, imports, exports, use, disposal and leakage of plastics in the US in 2017. Width of flows scaled to mass (for reference: production of HDPE = 8.576 million metric tonnes). Colors correspond to polymer types (see legend). Numbers in parentheses refer to notes in table 1 of Heller et al 2020[41]. Note that the difference in mass between production (left side) and end-of-life (right side) in this 2017 snapshot represents a net addition to in-use stock. The detailed large figure can be checked in Appendix-A.

Box 3. Example: Scale of Reduction

Limited data availability often makes it difficult to estimate the potential scale of reduction from a given innovation. We've explored innovative approaches to estimating the use of plastics in specific sectors, and therefore the potential to reduce plastic use by displacing its use in that sector. Here we detail one approach based on the US Bureau of Economic Analysis Input/Output Accounts (https://www.bea.gov/data/industries/input-output-accounts-data). These data offer a comprehensive picture of the inner workings of the U.S. economy, showing production relationships among industries and commodities, based on economic exchanges. While input-output data are updated each year and provide information on 71 industry categories, detailed benchmark input-output statistics are further subdivided into 405 industries and produced roughly every five years. The detailed data is required for the level of resolution needed here, thus this assessment relies on data from the most recent year available, 2012 (available at: https://apps.bea.gov/industry/xls/io-annual/Use_SUT_Framework_2007_2012_DET.xlsx).

The supply and make tables present the commodities that are produced by each industry. The supply table extends the framework, showing supply from domestic and foreign producers that are available for use in the domestic economy in both basic and purchasers' prices. The use table shows the use of this supply by domestic industries as intermediate inputs and by final users as well as value added by industry. For more information on input-output accounts, see: https://www.bea.gov/resources/methodologies/concepts-methods-io-accounts.

Of interest in this analysis are the plastics-related commodities: "plastics material and resin manufacturing" (BEA Industry Code 325211) and the 10 commodities within "Plastics and rubber products" (BEA IC 326). First the dollar value of plastic resin required as input per dollar of industry output for each of the 10 "plastics and rubber products" can be estimated by dividing the input value by total industry output (in millions of USD), as seen in the following:

Table 3. Dollar value of plastic resin required as input per dollar of industry output for each of the 10 plastics and rubber products (BEA IC 326)

325211	2012 Plastic and resin manufacturing	Plastic packaging materials and unlanimated film and sheet manufacturing	Plastic pipe, pipe fitting and unlanimated profile shape manufacturing.	Laminated plastic plate, sheet(except packaging), and shape manufacturing.	Polystyrene foam product manufacturing	Urethane and other foam product (except polystyrene) manufacturing	Plastics bottle manufacturing	Other plastics bottle manufacturing	Tire manufacturing	Rubber and plastic hoses and belting manufacturing	Other rubber product manufacturing
		326110	326120	326130	326140	326150	326160	326190	326210	326220	326290
		14140	6350	558	2262	756	4843	19319	73	163	306
T018	Total industry basic output(basic value)	39372	15421	3543	8303	9437	12322	83550	21030	5277	18059
	Resin fraction of total	0.359138	0.411776	0.157494	0.27243	0.08011	0.39304	0.23123	0.00347	0.03089	0.01694

Next, the mass of resin used per industry output (in dollars) of each "plastic material" can be estimated using a price for plastic resin to convert the dollar ratio generated above into physical units of plastic used. Here, we've relied on historical market data from The Plastics-

-Exchange website (http://www.theplasticsexchange.com/Research/WeeklyReview.aspx). Weekly summary reports for the first 6 months of 2012 were downloaded, a weighted average price (weighted by quantity sold each week) for each resin was calculated, and then - because resin type is not detailed in the I/O tables - a weighted average price across resin types (again, weighted by quantity sold for each resin over the 6 months) was calculated. The "spot" price from the market summary reports was used. This resulted in an average price of \$0.67/lb (\$1.56/kg), which was divided into the "resin fraction of total industry output" to arrive at kg plastic resin per \$ total industry output for each of the "plastic material" commodities.

This result can then be multiplied by the \$ of plastic material commodities used in other industries/sectors to offer a coarse estimate of the number of plastics used in that industry. For example, if we were interested in knowing the plastics used in food service and drinking places (BEA Industry Codes 722110, 722211, 722A00):

Table 4. The plastics used in food service and drinking places (BEA Industry Codes 722110, 722211, 722A00)

	(from 2012 BEA Supply-Use Table)	Full-service restaurants	Limited-service restaurants	All other food and drinking places
BEA industry codes	Commodity Description	722110	722211	722A00
		[millions of US dollars]		
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	113	67	4
326120	Plastics pipe, pipe fitting, and unlaminated profile shape manufacturing	138	125	28
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	10	29	5
326140	Polystyrene foam product manufacturing	213	2520	142
326150	Urethane and other foam product (except polystyrene) manufacturing	511	1423	327
326160	Plastics bottle manufacturing	4	21	1
326190	Other plastics product manufacturing	460	641	67
326210	Tire manufacturing	84	38	7
326220	Rubber and plastics hoses and belting manufacturing			
326290	Other rubber product manufacturing	0	60	12
		metric tonnes plastic		
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	2.60E+04	1.54E+04	9.19E+02
326120	Plastics pipe, pipe fitting, and unlaminated profile shape manufacturing	3.63E+04	3.29E+04	7.37E+03
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	1.01E+03	2.92E+03	5.04E+02
326140	Polystyrene foam product manufacturing	3.71E+04	4.39E+05	2.47E+04
326150	Urethane and other foam product (except polystyrene) manufacturing	2.62E+04	7.29E+04	1.68E+04
326160	Plastics bottle manufacturing	1.01E+03	5.28E+03	2.51E+02
326190	Other plastics product manufacturing	6.80E+04	9.48E+04	9.91E+03
326210	Tire manufacturing	1.86E+02	8.44E+01	1.55E+01
326220	Rubber and plastics hoses and belting manufacturing			
326290	Other rubber product manufacturing	0	6.50E+02	1.30E+02
	total	195,828	664,056	60,600
	total (plastics only)	195,641	663,321	60,455

Disregarding the "rubber" plastic material commodities, summing the values in light pink in the above screenshot amounts to ~0.9 million metric tons of plastic utilized in food service and drinking places in 2012. This is ~1.5% of the total plastics used in the US.

Even though this approach relies on a number of simplifications, such as averaging resin prices, it offers a coarse scaling of the plastics used in specific sectors/industries and therefore provides some insight into the potential reductions from innovations.

3.5 Innovation Maturity Level

Since the data availability and critical problems are quite different among early and growth stage businesses, we make use of maturity level analysis in order to separate. When assessing a company for its sustainability performance, it is important to consider the maturity level of the company at that current state. Different maturity levels may offer varied amounts of information pertaining to the product, technology, or service.

Technology Readiness Level (TRL) is a measurement system used to assess the maturity level of a technology. But evaluating emerging or mature technologies within a developing or growing company may pose challenges. Thus, it is critical to indicate whether the company is in **the early, growth, or mature stage**, in order to align with the evaluation framework, and indicate the process for assessing sustainability.

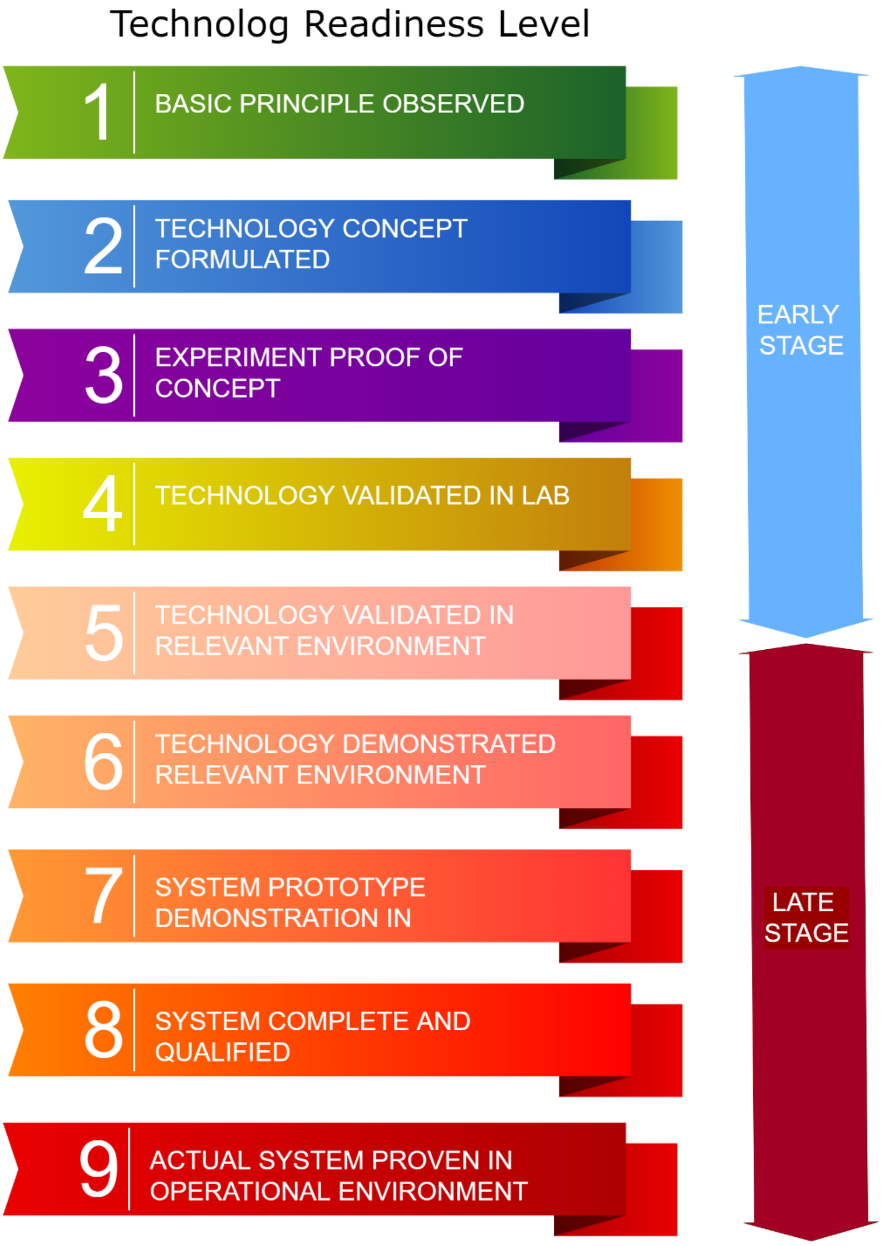

Figure 8. Different TRLs with brief descriptions and seperation of early stage and growth stage

(modifed from TWI[42])

Figure 8 shows the readiness levels assigned to the two categories used in the tool. In general, if the opportunity is in production and available in the market (even as a prototype in a trial market), data should be available to initiate sustainability focused evaluations.

3.6 Environmental Performance: Certifications

3.6.1 Basis / Overview

Many companies will use certifications in their product labeling and marketing to demonstrate environmental performance and attributes of their service or product. Certification is a voluntary process which can provide useful environmental information for evaluating a company and its products. Some commonly used certifications are listed in Box 4.

Certification is a good indicator for investors. There are many studies showing that companies with certifications can have better performance in certain aspects. For example, Treacy et al[43] and Mokhtar & Muda[44] demonstrate that both environment related certifications (ISO 14001 etc.) and quality certifications (ISO 9000 etc.) correspond with long-term company performance, including:

- Fraction of professional employees
- Cost Efficiency
- Return on Assets
- Supply Chain Efficiency
- Limitations

Having certifications can be a good indicator, but certifications alone cannot guarantee the overall sustainability of the company. Most certifications focus on a single property or aspect of a product or business, instead of evaluating the whole system, so companies can acquire multiple certifications regarding their supply chain and products to help demonstrate environmental performance.

3.6.2 Guidance Criteria

Certifications do not guarantee sustainable products, but it can provide useful performance information. Based on the application and limitations of certifications, we can expect following questions to be considered when evaluating the innovations:

- **Has the company acquired appropriate certifications to distinguish and help validate environmental attributes about their service or products?**
  Due to both application and limitation of the certification, a company needs different certifications for the different components of their supply chain. The following example lists certifications that a company utilizing compostable material might have:

- Certifications through entire supply chain
    - Energy Consumption: Renewable Energy Certificates (EPA)
    - Water Consumption: WaterSense® Product Certification (EPA)
    - Environmental Impact Management:ISO14000 Certification
    - Quality Management: ISO9000 Certifications
- Raw material production phase: Biomass Cultivation: Organic Certification (USDA)
- Transportation: Green Transportation: Certification for Sustainable Transportation
- Products Manufacture Phase: Environmental Safety and Health: CRADLE TO CRADLE
- Product Safety: SAFER CHOICE (EPA)
- End-of-life treatment phase: Biodegradability: ASTM 6400 certification

- **Do the certifications demonstrate critical product/service characteristics being claimed?**
  Sometimes, the company may have a certification that is completely inappropriate for their product. For example: claiming "home compostable" whereas the certification acquired for a biodegradable material is valid for industrial composting. Investors and analysts need to recognize possible misleading characterizations made.

Box 4. Making Sense of Certifications

Certifications offer a standardized measure of performance in a specific category or aspect. Increasing numbers of certifications concern sustainability issues, both social and environmental in nature. It is important to recognize, however, that as a market-based mechanism for addressing social and environmental challenges, standards can vary considerably. An understanding of the standards applied in a given certification can help in interpreting its meaning for a product or business. Acknowledging the certifying body can also help in assigning credibility and trust in a certification: in general, independent, non-profit or governmental certifying bodies are more likely to maintain unbiased standards than, say, organizations closely associated with industry groups, but this is certainly not an absolute rule, and certifications should be examined individually.

Certifications can also be narrowly defined on a specific aspect or property, and it will be important not to conflate this with broader sustainability claims. Further, some certifications can be based on theoretical performance without demonstration of real-world results. An example of this might be a certification of biodegradability or compostability that is based on material properties without an actual demonstration of performance.

Table 5 lists a number of popular certifications, organized into topical categories, that may be relevant to plastic waste reduction innovations. This listing is by no means exhaustive, and does not represent a vetting or endorsement of the examples, merely a representation of certifications that may be of interest.

Table 5. Typical certification categories

Certification Category	Examples	Certifying body	coverage	For more information...
Business strategy	B Corp	B Lab (non profit)	Social/environmental performance, transparency, accountability, balancing profit and purpose	https://bcorporation.net/
Energy Savings	Energy Star	US EPA/ DOE	Energy efficiency	https://www.energystar.gov/
Environmental Management	ISO 14000	Numerous registrars based on standards set	Minimizing negative env. impacts	https://www.iso.org/iso-14001-environmental-management.html
GHG Emission	Product Carbon Footprint Label	Carbon Trust (company)	Multiple levels of emission declarations	https://www.carbontrust.com/what-we-do/assurance-and-certification/product-carbon-footprint-label
	Science Based Targets Initiative	SBTi (non-profit partnership)	Commitment to emission reduction path	https://sciencebasedtargets.org/
	Climate Neutral Certified	Climate Neutral (non-profit)	Footprinting, offsetting, reductions	https://www.climateneutral.org/
Water Savings	WaterSense Certification	US EPA	Water use efficiency	https://www.epa.gov/watersense
Biodegradability	BPI certification	Biodegradable Products Institute	biodegradability/compostable	https://bpiworld.org/
Plastic Recycle	Postconsumer Resin (PCR)	Assoc. Of Plastic Recyclers (3rd party certified)	Post-consumer recycled content	https://plasticsrecycling.org/apr-pcr-certification
	Mass Balance Certification	American Chemistry Council standards (3rd party certified; e.g., ISCC) Textile Exchange	Certifying recycled content claims	https://plastics.americanchemistry.com/recycling-and-recovery/Mass-Balance-Certification-Principles-2020.pdf
	Recycled Claim Standard (RCS)		Recycled input & chain of custody	https://textileexchange.org/standards/recycled-claim-standard-global-recycled-standard/
	Global Recycled Standard (GRS)			
Quality assurance	Recycled plastic Component recognition	UL	Assures recycled plastic is substitute for virgin	https://www.ul.com/services/recycled-plastics-testing-and-certification

3.7 Environmental Performance: Life Cycle Assessment

3.7.1 Basis / Overview

"Life Cycle Assessment (LCA) involves the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." (ISO 14040-2006)[45] Refer to Box 5 for more information on LCA.

3.7.2 Guidance Criteria

As a modeling tool, LCA is a valuable tool for quantitatively analyzing environmental performance but the quality of analysis depends on various factors such as choice of methodology, design of system boundary, and assumptions. LCA is a standardized tool but it can be overwhelming to a non-LCA expert. Some of the important questions that should be considered when reviewing an LCA include:

- **Was the LCA conducted by a reputable consultant or other LCA expert?**
  This helps assure that standard procedures and best practices were followed. Internal staff or partners certainly can conduct a high quality LCA, but this is an area where experience and background expertise can be highly beneficial.

- **Was the LCA peer reviewed in accordance with ISO standards?**
  This offers additional confidence in methods and, per ISO standard requirements, it means that results are appropriate for public communications and comparative assertions.

- **Are the functional unit and system boundaries appropriate for the product/system and comparisons?**
  This assures that all relevant processes and life cycle stages included. Both functional units and system boundaries can strongly influence final results, and interpretation requires a solid understanding of both. For more explanation and examples, please refer to Box 5.

- **Has data quality been taken into consideration in interpreting results?**
  This recognizes that uncertainty in data can cloud assessment conclusions. Proper interpretation of LCA results should consider the quality of data used in the assessment and qualify conclusions appropriately. For example, if data includes high uncertainty, or does not reflect the geographic or temporal scope appropriate for the study, this must be acknowledged and conclusions must be drawn with added precaution.

- **Have uncertainties in LC impact assessment methods been taken into account in interpreting results?**
  There are various impact categories that are easily calculable via LCA databases and implementing software, but the certainty and assumptions necessary in developing these methods vary greatly. Less certain impact categories can include: human toxicity, ecotoxicity, eutrophication, and acidification. When

dealing with these categories, care must be taken in drawing conclusions from small differences.

- **Have sufficient uncertainty and sensitivity assessments been performed to consider an expected range of real-world situations?**
  This assures conclusions are robust across real-world variabilities likely to be encountered. Especially when the LCA is initially conducted using data from lab-scale or early start-up production, it's important for the study to consider likely parameters or uncertainty encountered in scaled up production.

Box 5. Life Cycle Assessment

Life cycle assessment (LCA) refers to the process of compiling and evaluating the inputs, outputs and potential environmental impacts of a product system throughout its life cycle[45]. In other words, it is a systematic accounting method based on a standardized framework and terminology that is used to quantify the effects on the environment from the systems and stuff that meet our human needs. The focus in LCA is on a given product, process or service, and may consider a number of different environmental impact indicators.

LCA is complex: it often requires modelling of complicated systems and biophysical processes. It demands large amounts of data, often data that simply are not available. While LCA can potentially encompass multiple environmental factors, often resource and data availability dictate a focus on a few key indicators such as greenhouse gas emissions or water use. Assumptions are required to overcome limitations in data and other uncertainties. The LCA method is intentionally flexible to accommodate a wide range of applications, scopes and inquiries. Sometimes assessments are conducted at more of a "scan level", as not all questions require a completely thorough accounting of every detail. Because of all of these limitations, the depth, breadth and quality of studies called "life cycle assessment" vary widely. A good LCA is a difficult and wonderful thing; but it is important to recognize that not all LCAs are created equally.

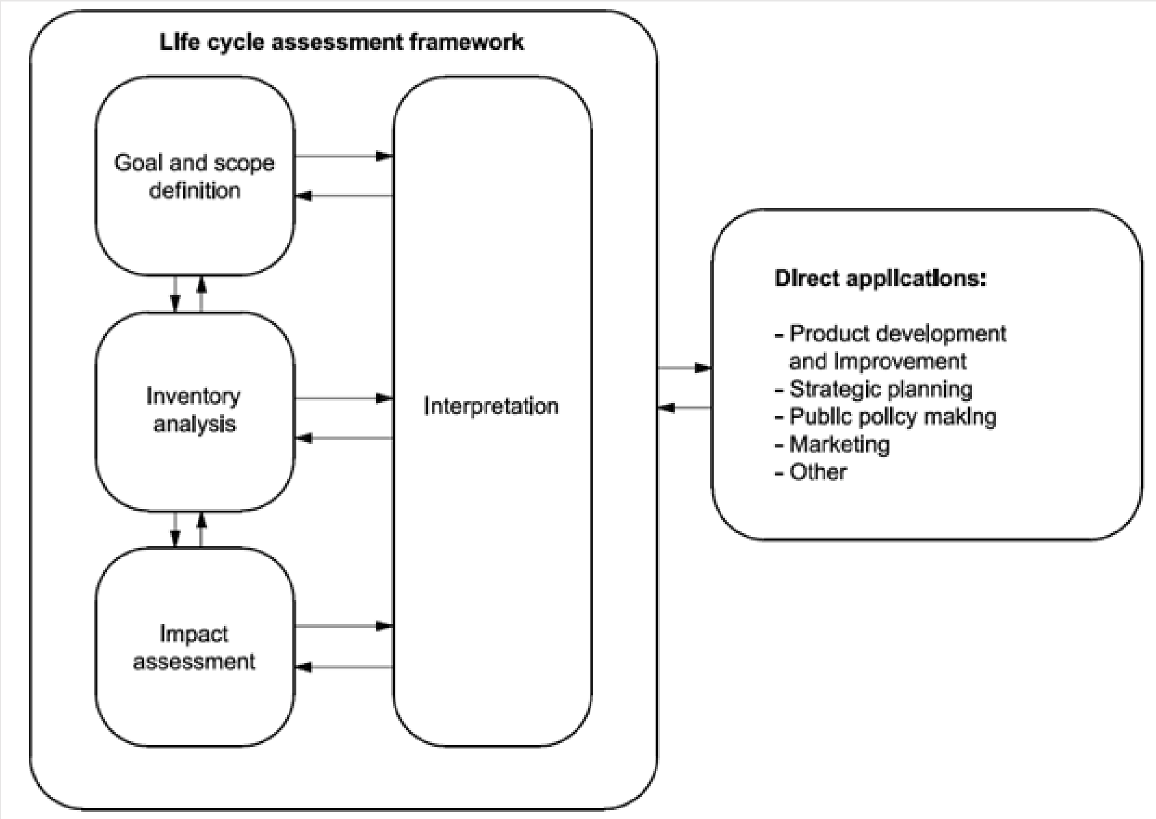

Figure 9. The typical life cycle assessment framework.

The general methodological framework for LCA is commonly illustrated as in Figure 9. Typically, the workflow is from top to bottom, with interpretation occurring throughout. However, the back-and-forth arrows demonstrate the iterative nature of LCA: often information about a system is gained in a later phase that requires the practitioner to revisit and reconsider choices made previously. Numerous texts, including the ISO standards themselves, detail the approach and stages of LCA[45, 46, 47]. Here we offer only a brief orientation.

Despite standardization, LCA remains a rather fluid methodology, capable of examining a wide variety of system types. This also means, however, that fully understanding and interpreting the results of an LCA requires an appreciation of the specific methodological choices employed. Much of the LCA procedure is defined and influenced by the specific question to be examined and the context around answering that question. It is in the **goal and scope definition** phase where that question is defined as clearly and explicitly as possible, along with the intended application, the reasons for conducting the study, and the intended audience. Central to this phase is defining the function of the system, as this becomes the basis for comparisons and reporting. LCA is a relative accounting method, such that results are given relative to a quantified definition of the system function, called the functional unit. For example, comparing a natural gas fired electricity generation plant directly with a solar panel makes very little sense. However, a well-defined function, say "supplying a MW of electricity over one month," allows a meaningful comparison of otherwise disparate systems. The functional unit also permits meaningful comparisons-

-between different stages of the life cycle: for example, LCA could describe how environmental emissions associated with the manufacturing of an electricity power plant compare with those from operation.

Inventory analysis, the second phase of LCA, involves "the compilation and quantification of inputs and outputs for a product throughout its life cycle"[45]. Inventory analysis is often very data and calculation intensive. In the standard LCA approach, known as process-based LCA, the life cycle under study is divided into unit processes. These include things like coal mining, steel production, assembling and producing an LED light bulb, operating an electric tea kettle, transporting by semi-truck, or recycling waste PET plastic. In LCA, a unit process is typically treated as a black box that converts a collection of inputs into a collection of outputs. Inputs include products (from other processes), natural resources (minerals and ores, energy carriers, biotic resources, land), or waste to be treated. Outputs also include products, waste for treatment, and residuals to the environment such as air, water and soil pollutants, and waste heat. Inventory analysis involves quantifying the inputs and outputs of interest across each unit process and the interconnections between each that form the product's life cycle. Digital databases and dedicated LCA software can greatly aid in harmonizing this complex and exhaustive accounting. Life cycles in theory can be infinitely large: there is almost always an additional upstream input that also requires materials and resources. This is addressed in process-based LCA by assigning a cut-off criterion, a point where additional contributions are negligible to the results of the study. Another perennial challenge encountered in the inventory analysis phase occurs when a process that cannot be further divided produces several co-products. Take, for example, the production of soy oil. Soy oil cannot be produced without also producing soymeal, which also has economic value. The upstream impacts leading to oil refining, including the agricultural production of soybeans, must somehow be allocated to the co-products. There are a number of approaches to doing this, and ISO standards offer a suggested prioritization of those approaches, but rarely is there a "right" answer and it becomes a methodological choice within the study. Debates on the relative merits of these approaches can be left to LCA practitioners and experts, but all who interact with LCA should appreciate that such choices can influence the results of an LCA.

The outcome of an inventory analysis can be dozens, hundreds, or even thousands of resource and emissions flows. What does these mean? What are the impacts on the environment? This is the purpose of the **impact assessment** phase. Environmental impacts are divided into categories, such as climate change, eutrophication, toxicity, water use impacts, and fossil energy depletion. The impact categories of interest and relevance to a particular study are defined in the Goal and Scope phase. Environmental impacts typically involve a cascading series of causal mechanisms. For example, an emission of greenhouse gases leads to changes in the composition of the atmosphere, which leads to a change in the radiation balance, which contributes to a change in the temperature distribution, which leads to changes in climate, which can affect ecosystems and human activities, etc. Scientists in chemistry, meteorology, ecology, and beyond have developed models to represent such causal relationships, but in general, the further along the causal chain, the more uncertain and contentious these predictive models become. Choosing to characterize an environmental impact earlier in the causal chain as a midpoint impact indicator, such as global warming potential reported in carbon dioxide equivalents, introduces less-

-uncertainty. In some applications, however, the communicative benefit of a more intuitive endpoint impact indicator, such as loss of human life years, may outweigh the added uncertainty. In addition, the causal chains of various environmental impacts typically converge on a few "areas of protection" at the endpoint, allowing more direct comparisons (albeit with greater uncertainty) and aggregations of disparate indicators.

A variety of impact assessment methods have been developed for use in LCA, and these are typically implemented in LCA software, making their application fairly straightforward. Interpretation of impact assessment results, however, can be challenging and often requires an understanding of and experience with the methods employed. Further, there is little specification or guidance in choosing impact assessment methods, and differing methods can and do offer different results for the same impact category. Again, discussion of the relative merits of various assessment methods is beyond the scope of this text, but it is important to recognize that such choices can matter. Thoroughly conducted LCAs will demonstrate and discuss variability introduced by assessment method choice.

The **Interpretation** phase involves evaluating the findings of inventory analysis or impact assessment (or both) in relation to the defined goal and scope in order to reach conclusions and recommendations. It generally involves an acknowledgement of limitations and assumptions, assessments of data quality and completeness, as well as sensitivity analysis aimed at characterizing the reliability and robustness of conclusions. This occasionally requires returning to decisions, analysis or data collection addressed earlier in the LCA in order to refine and improve the study. Conclusions are drawn and recommendations made by putting results in the context of decision-making and limitations.

Strengths

LCA was initially developed to evaluate and improve products, particularly in product development, and the method excels in this role of identifying unexpected opportunities to reduce impacts, or unexpected consequences of a particular design choice. A classic example of this is Procter & Gamble's LCA of household laundry detergents in the early 2000s. After determining that the overwhelmingly dominant impacts associated with laundry detergents arise not from resource extraction or packaging manufacture, but from the energy required to heat water in the use phase, P&G developed a new detergent that could clean just as effectively in cold water[48].

As implied earlier, LCA can also be a valuable way of comparing different systems or products that offer the same service or function, but involve dramatically different processes. Classic examples include comparisons of glass and plastic beverage containers or paper and plastic shopping bags.

The strengths of LCA include:

- Evaluating the environmental consequences associated with a given product or process.
- Highlighting "hot spots" in a product or process life cycle that warrant focused attention. Where are the largest burdens?

- Analyzing the environmental trade-offs associated with one or more products or processes. Trade-offs can occur between stages of a product life cycle, between environmental impact categories, between societies/geographic regions, or between generations.
- Identifying unexpected consequences of a product or innovation.
- Identifying “burden shifts” between environmental impact categories or across life cycle stages. In other words, does addressing an environmental problem at one stage simply move the impact somewhere else?
- Comparing the potential impacts between two or more products or processes.

LCA has found application in:

- product development and improvement
- strategic planning
- marketing

Weaknesses

LCA is a powerful tool. But it can’t do everything. Understanding the limitations of LCA is critical to identifying proper applications. LCA offers a relative look at potential environmental impact that can help inform decisions, but must be balanced with other considerations and cannot answer absolutely whether a product is sustainable or not. It can be data intensive and costly, and only proxy data may be available.

- Process-based LCA is typically data intensive, which often means that it is time-consuming and costly. It can offer extremely valuable insights that, when implemented, in many cases translate into direct environmental and financial savings and as such, LCA can be a very sound investment. Still, these intensities can make it inaccessible for some stakeholders and applications. That said, there often is value in simplified approximations – “back-of-the-envelope” or scan-level LCAs based on a limited scope and data – but interpretation must carefully account for these limitations.
- LCA can help inform decision-making. Ultimately, however, it must be taken into account with a suite of other considerations including costs and social implications. LCA can help identify an opportunity, but additional tools and protocols are likely needed to help inform and support action.
- LCA offers an indication of potential environmental impact. It is not a measure of impact that has occurred in the absolute sense. This is perhaps only a weakness if it is misinterpreted.
- LCA is a relative assessment method. As a consequence, and perhaps contrary to popular belief, LCA cannot tell if a product is "sustainable" or "environmentally friendly." LCA can only indicate if product X is "more sustainable" or "more environmentally friendly" than product Y, or that the use phase is the "least sustainable" or "least environmentally friendly" part of the life cycle for product Z.

- Most LCA datasets are based on industry averages, or sometimes even specific examples. As such, they often do not represent the specifics of a particular product chain or fully capture the variability inherent across industries and economies.
- The analytical structure of LCA assumes linear scaling of technologies. This assumption means, for example, that producing 1 kg of steel has the same impact per kg as producing 5 million kg of steel. In some applications, consequential LCA is an attempt to address this limitation.

3.8 Technology Specific Considerations

In this section, we move from general sustainability criteria for business models to specific technology considerations. The tool will go through the basic information and key guidance criteria for Reuse & Refill, Alternative Materials, Innovative Design, and Recycling respectively.

3.8.1 Reuse & Refill

Overview

The use of reusable containers for food or beverages may be a practical solution as a replacement for single use containers. Business-to-Business (B2B) reusable logistics packaging is relatively mature and most new reuse and refill innovations center around a business to customer (B2C) service.

Consider the following points for evaluating a reuse and refill opportunity:

- Some form of collection, return transportation, and cleaning is required and is considered additional to the incumbent solution.
- Reuse may introduce new plastic or other non-plastic material into a market.
- While size and shape may be maintained, package mass may increase and may impact processing (e.g., filling), logistics, and use.
- A comparative life cycle assessment is encouraged to establish the break-even point where further reuse will reduce total environmental impact (i.e., waste, energy, GHG) relative to incumbent single use option.
- End-of-life of the reusable package must be considered.

Guidance Criteria

- What is the break-even number of reuses where total energy use and GHG emissions are reduced versus a single use package?
- How will the environmental impact change when renewable energy is widespread?
- Will collection, return transportation, and cleaning of reusable packages increase the use of fossil energy or strain a water scarce region?
- Does new plastic or other non-plastic material used for the package have a

robust recycle market or viable compost solution?
- Will a heavier package pose problems upstream, downstream or in use?

Common Sources

Companies should have a comprehensive description of their reuse system in their sustainability or business plan. Information on this can typically be found on their website and must be included in their product press releases. If the company is in its early stages, publicly available information may only include assumptions and a brief description of their reuse system. In growth stages, detailed information of the reuse system should be available through their sustainability report or LCA.

3.8.2 Alternative Materials

Overview

In this application, an alternative material is defined as a non-synthetic polymer material as a replacement for the plastic material while maintaining equal or better performance. The available alternative material for plastic replacement can be generally divided into renewable and non-renewable materials.

Intrinsic Property

Intrinsic Properties directly affect the quality of alternative materials to function as a substitution of conventional plastics. Some examples are:[49]

- Chemical Resistance
- Physical Resistance
- Thermal Resistance
- Liquid Permeability
- Thermal Plasticity
- Flexibility

Abundance

The availability of the renewable feedstock dictates the extent of market penetration. The inbound logistics to a processing plant can have a negative impact on cost and greenhouse gas emissions.

Composting

The current composting standard can be divided into industrial composting and home composting (see Table 6).

Table 6. Comparison of standards for industrial and home composting

Process	Test condition and minimum performance standards	
	Industrial composting (EN13432)	Home composting (Vincotte Certification)
Biodegradation	Test at 58 °C in 180 days Biodegration minimum 90%	Test at 20 - 30 °C in 365 days Biodegration minimu 90%
Disintegration	Test at 58 °C in 90 days	Test at 20 - 30 oC in 180 days
	Sieve 2mm mesh	Sieve 2mm mesh
	Disintegration > 90%	Disintegration > 90%
	Maximum 10% of dry weight allowed to be retained by 2mm sieve	Maximum 10% of dry weight allowed to be retained by 2mm sieve
Designation	Din Certco/OK Compost	OK Home

It is important to understand which classification an alternative material in the target application apply.

A life cycle assessment is appropriate to evaluate the impact of the cradle to gate supply chain, any land change impacts, and the impact on or displacement of food crops.

Guidance Criteria

- **Do the intrinsic properties of the alternative material(s) qualify as substitutes for displaced conventional plastics?**
  As mentioned above, the intrinsic property is the most important factor that affects the function of alternative materials. The intrinsic properties of a material need to meet the basic requirement of commercial application. For example, an alternative package for food should be qualified in terms of shelf life and durability, sealing strength, printability, flexibility.

- **For compostable materials, what are the required composting conditions?**
  Composting conditions can be divided into home composting grade and industrial composting grade. Under most conditions, home composting grade (compost in normal soil) may have advantages over industrial composting grade (high temperature required). The company should give a clear description of the composting condition.

- **Does the production of biomass used in an alternative material regenerate quick enough and does it compete with other critical land uses?**
  For bio-based material, we need to consider the regeneration speed of the agriculture or raw material. According to the basic concepts of sustainable development, consumption of renewable resources needs to be slower than its regeneration rate. At the same time, we also want to avoid competing with other important uses. For example, we don't want to result in food price increases due to competing with food agriculture.

3.8.3 Innovative Design

Overview

Besides changing consumption patterns or replacing material, some innovations aim to eliminate the use of plastic and packaging materials by reconsidering product design. Such innovations are currently popular in the personal care and home cleaning products sectors, for example, by using soluble tablets to replace liquids avoiding the need for plastic containers.

In such cases, the environmental performance of the new design relative to what it is replacing may not be obvious: impacts can easily shift to a different stage of the life cycle (e.g., from material manufacturing to transportation) or to a different impact category (e.g., from eco-toxicity to GHG emissions). An LCA study comparing the new design with the incumbent product/service will offer valuable perspective.

Short of a full LCA, useful Life Cycle Design guidelines and principles have been developed using life cycle thinking and industrial ecology concepts. These are best implemented in early stages of the redesign process and fully incorporated into the product/service development. A summary of some of these guidelines can be found in Box 6.

Guidance Criteria

- **Does a comparative LCA demonstrate performance advantages over the status quo?**
  A good innovative design will demonstrate advantages over traditional products in terms of environmental benefits, which can be quantified through LCA. Some companies that provide special plastic reduction services will need to specify how they change customers' behavior and what impact will be brought by these changes.

Box 6. Life Cycle Design principles

Life cycle design involves applying and incorporating life cycle thinking to the overall design process. This means considering the upstream and downstream influences and impacts of a product or service: from the extraction and processing of materials and fuels required to the operation or use of the product or provision of service, through to the disposal of materials or waste at the end of use. The aim is to decrease the burden or impact on the environment of the final designed product/service. Life cycle design, sometimes referred to as life cycle engineering, emerged in the mid-1990s alongside developments in life cycle assessment and other industrial ecology concepts. The principles and strategies listed below date from these early developmental days, but directly reflect many of the principles now forwarded under frameworks such as circular economy (see Box 1). Additional guidance for implementing these principles can be found in the original references.

Environmental principles and criteria for Life Cycle Design (adapted from [50])

- Achieving environmental efficiency / optimal function
- Saving resources
- Using renewable and sufficiently available resources
- Increasing product durability
- Designing for product reuse
- Designing for material recycling
- Designing for disassembly
- Minimizing harmful substances
- Developing environmentally friendly production
- Minimizing environmental impact of product in use
- Using environmentally friendly packaging
- Implementing environmentally friendly disposal of nonrecyclable materials
- Implementing environmentally friendly logistics

Reduced material intensity	• Conserve resources
Process management	• Process substitution • Process energy efficiency • Process materials efficiency • Process control • Improved process layout • Inventory control and material handling • Facilities planning • Treatment and disposal
Efficient distribution	• Choose efficient transportation • Reduce packaging • Use lower impact/reusable packaging
Improved management practices	• Use office materials and equipment efficiently • Phase out high-impact products • Choose environmentally responsible suppliers and contractors • Label properly and advertise demonstrable environmental improvements

Life Cycle Design strategies, Contd. (adapted from [51])

Product life extension	• Extend useful life • Make appropriately durable • Ensure adaptability • Facilitate serviceability by simplifying maintenance and allowing repair • Enable remanufacture • Accommodate reuse
Material life extension	• Specify recycled materials • Use recyclable materials
Material selection	• Substitute materials • Reformulate products
Reduced material intensity	• Conserve resources
Process management	• Process substitution • Process energy efficiency • Process materials efficiency • Process control • Improved process layout • Inventory control and material handling • Facilities planning • Treatment and disposal
Efficient distribution	• Choose efficient transportation • Reduce packaging • Use lower impact/reusable packaging
Improved management practices	• Use office materials and equipment efficiently • Phase out high-impact products • Choose environmentally responsible suppliers and contractors • Label properly and advertise demonstrable environmental improvements

3.8.4 Recycling

Plastic recycling is the process of recovering and reprocessing plastic waste into a secondary material that can be used in the production of new components and products[19]. Although "mechanical recycling" is most commonly associated with plastic recycling, there are in fact four distinctly different pathways for maintaining and extracting technical value from waste plastics:

1) Primary Recycling (Re-extrusion)
2) Secondary Recycling (Mechanical Recycling)
3) Tertiary Recycling (Chemical or Feedstock Recycling)
4) Quaternary Recycling (Energy Recovery)

Primary recycling usually involves the post-industrial or pre-consumer waste stream, with only some cutting and trimming processes required due to the homogeneity of the material. This market is mature, and in this tool, we will consider pathways 2) through 4), which are often called post-consumer plastic waste (PCPW) treatment.

Box 7 explains a waste management hierarchy as applied to plastic waste, offering clear preference to mechanical or chemical recycling over energy recovery in the form of fuels or electricity generation.

Box 7. Plastic Waste Management Hierarchy

Sustainable plastic management is aimed at minimizing the environmental damage that comes from plastics. Sustainable plastic is "plastic that is fit for purpose, consumes minimal resources, generates minimal waste, and involves minimal risks to social and environmental systems"[53]. There are several different ways to determine which method is more sustainable or less environmentally harmful, but the core concept is similar, just as Figure 10 illustrates.

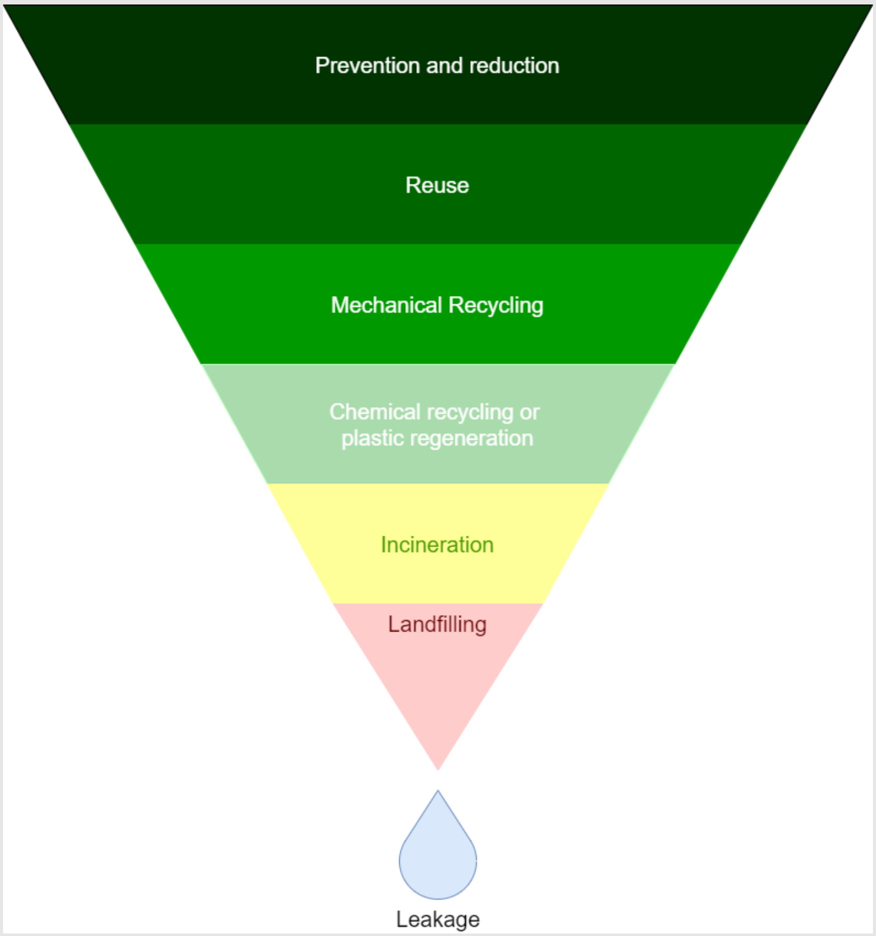

Figure 10. The typical waste hierarchy model of plastic waste management (BCG)[54].

Prevention and Reuse are preferable because they directly reduce the chances of plastic reaching end-of-life treatment. Least desirable in the case of plastics is leakage into the natural environment where plastics can negatively impact terrestrial and marine ecosystems. Only slightly preferred over leakage is loss to landfill, which represents a permanent loss from our technical economy (for the foreseeable future, at least, until landfill mining becomes economically viable). In the middle are the possible recycling pathways considered here, with quaternary recycling (incineration or energy recovery) being a last resort effort to recover value from waste plastics. Mechanical recycling is currently preferred over chemical recycling as it typically is less energy intensive, but innovations in chemical processing could change this. Mechanical recycling is currently burdened with the complications associated with separating a very diverse plastics waste stream, with impurities often leading to lower quality secondary material and thus downcycling (reduction in material value relative to the virgin material).

A) Mechanical Recycling

Mechanical recycling involves sorting plastic waste of similar polymer type, then processing them into secondary raw materials to be used to make new products. Since many companies only focus on one of these two stages, PRISET separates them and gives guidance on each.

A.1) Mechanical Recycling – Stage 1: Sorting

Overview

Continuous technology improvements in collecting and sorting have been created, making it possible to filter out plastics among other materials, and even sort the most high-value plastics among heterogeneous waste material. For more information, please refer to Box 8. In general, efficiency is an important parameter in determining relative sustainability of sorting processes. Sorting efficiency is measured by:

- # of pieces / unit time
- Different types of polymer to be treated / unit time
- Sorting loss % or error rate

Box 8. Basic Sorting Technology Information

Different sorting methods have advantages and disadvantages. Below are current existing methods of mechanical sorting:

- (Near) Infrared technique separates most plastics, but cannot identify carbon black tinted plastics and items with labels made of differing materials.
- The X-ray method is similar to the function of infrared technique, and is mostly useful in PVC separation.
- Air sorting and electrostatic sorting are techniques that require plastics to be as small as flakes or particles first.
- Melting methods can only separate two types of plastics at a time.
- Other types of sorting processes include wet and chemical sorting methods, but these processes may have extra limitations and more environmental burdens beyond the previously mentioned methods.

Some key questions to keep in mind for sorting technology include:

- Does the solution effective deal with dust and dirt?
- How does the solution deal with small differences in particle gravity?
- Could the solution deal with paint, coating, and additives?

Guidance Criteria

- **How is the innovation unique compared to the incumbent collection and sorting systems?**
  Since there are various kinds of collection and sorting systems dealing with plastic waste issues, it is critical to understand what the unique key characteristics are. Some examples may include sorting more than three types of polymers or using a more intelligent tracking system. The focal firm should also address the limitations that traditional methods encounter, such as efficiency and scale of sorting, upstream and downstream market availability, and challenges with labels, and additives in polymers.

- **What is the targeted waste stream?**
  Current plastics recycling markets are dominated by PET, PE, and PP; because there is high demand for secondary material of these resin types, they represent the highest value to material recovery facilities (MRF) and other resin types are lower priority or even primarily considered a 'contamination' in the waste stream. Thus, innovations that focus on identifying and separating resins with lower market value will not only improve the quality of dominant recycled plastic streams but also support the development of new solutions for harder-to-recycle resins.

- **Is the sorting efficiency improved compared to the incumbent or competing sorting and collection process?**
  Efficiency is the core metric of competency when it comes to sorting and collection. When measuring efficiency, pay attention to the units and their embedded assumptions. Ideally, we want both the sorting rate and available types of sorted polymers to be a larger number, but we also need to take into consideration other elements, such as the potential scale and energy intensity.

- **Are there any social behavioral changes required to complement the new sorting process? What efforts will be made to support this change?**
- **Are there any regulatory measures conflicting with this business or service model?**
  Plastic sorting and collection is deeply impacted by social and governmental behaviors. For example, local or federal restrictions on polymer recycling and sorting regulations, collection routes, labeling and additive standards all will impact performance.

A.2) Mechanical Recycling – Stage 2: Processing

Overview

Assuming post-consumer plastics are perfectly sorted and lacking contaminants, the principal challenge in mechanically reprocessing plastics is that polymers degrade under certain conditions including heat, oxidation, light, ionic radiation, hydrolysis, and mechanical shear. This typically results in lower quality recycled material, but can also

hinder the processing itself. Thermal-mechanical degradation can occur during reprocessing, whereas other forms of degradation typically occur during the lifetime of the product. Contaminants, both designed (i.e., intentionally added such as colors, plasticizers, processing aids, labels, inks) and created (i.e., dirt, residues, incomplete polymer sorting) introduce additional challenges in reprocessing.
Ultimately, a recycling process must yield a secondary product that is marketable, and to be truly sustainable, it should displace the use of primary (virgin) materials. Barriers to such displacement include material quality (intrinsic properties) but also price/cost.

Guidance Criteria

- **How is the innovation unique compared to the incumbent process?**
  If the technology is new or recently introduced, the focal firm should explain the details of the process concisely. If the innovation aims to reduce cost or improve scale, the focal firm should describe how the new system works compared to incumbents.

- **How much of the collected material becomes utilized or utilizable recycled polymer?**
  The effective recycling rate is a key driver in determining the performance of processing in mechanical recycling. At the least, the innovation should outcompete the incumbent utilization numbers. Using the **Circular Economy** and **Life Cycle Assessment** criteria, evaluators will gain a deeper understanding how quality of recycled plastics determine the utilization of collected material and analyze the end-of-life sustainability results compared to its single-use counterparts for instance.

- **Does the process maintain sufficient material quality and durability?**
  This is another key driver in determining the performance of processing in mechanical recycling. As stated before, closed-loop processes can help to ensure the maintenance of quality and durability compared to single-use counterparts.

- **What is the environmental impact?**
  Using the **Certifications** and **Life Cycle Assessment** criteria, evaluators can understand the environmental impacts of both sorting and processing stages in mechanical recycling of various plastics, especially with respect to energy intensity, toxicity of applied solvents, etc.

B) Alternative Recycling

Overview

Two main alternative recycling methods include energy recovery and chemical recycling. Chemical recycling is any process that chemically reduces a polymer so that it can eventually be processed and remade into new plastic materials that go on to be new plastic products. Energy recovery is the process of converting municipal solid waste into various forms of energy, such as electricity or steam for district heating or industrial customers. It is often known as “Waste to Energy.”

There are dozens of different technologies that perform chemical recycling; thus, we leave it to outside specialists in the chemistry industry to analyze these efforts. However, one point to emphasize is that the chemical recycling industry is a nascent stage, and broad and significant innovation is possible. If we consider the four quadrants analysis including technology maturity and market maturity[56], most chemical recycling innovations fall into “emerging technology enters emerging markets”.

For energy recovery, the first factor to consider is the waste hierarchy, i.e., is there enough evidence to support that the plastics cannot be prevented, reused, or recycled in another method? Energy recovery is also sensitive to conversion efficiency.

Incineration and chemical reactions can produce harmful substances that must be controlled from release. Therefore, evaluators need to consider:

- % reduction of landfill
- % reduction of fossil fuel usage
- Emissions of $CO_2/NO_x/SO_x$ and particulate matter
- Emissions of toxic substances

Specific to thermal recycling, evaluators should consider:

- End-of-life operations such as flue gas cleaning and residue treatment
- Feed preparation (e.g., treatments with coal) in co-combustion

Guidance Criteria for Chemical Recycling

- **What is the scalability / efficiency / conversion rate of the chemical recycling process?**

- **What is the scope and limitation of the innovation application?**
  Certain chemical recycling innovation can be only applied to specific types of plastics. At the same time, the innovation also have limitations on the ability to handle contaminated plastics and mixed waste.

Guidance Criteria for Energy Recovery:

- **Does the sourcing/sorting process ensure that energy recovery is the best use?**
  In plastic waste recycling, energy recovery should be the last choice because of the low utilization and emissions on the environment. Therefore, providing evidence on the sources of polymers is significant.

- **Is the waste treatment capacity improved (e.g., in tons / unit time)?**

- **Is the energy recovery rate improved and economical (e.g., in MJ or kWh / ton of waste)?**

4. Case Study - CupClub

In this section, we introduce a case study to indicate the use of PRISET tool, as well as giving some suggestions after evaluation.

4.1 Case Overview

CupClub is a company partnering with businesses and retailers to service retail cafes, in-house cafes, canteens, restaurants, coffee or tea points. They offer reusable cups to customers who can return the cups at multiple drop-off points. The cup is tracked by RFID systems. The company incentivizes the user to return the cups within a set time span. If this does not incur a late fee is charged. Figure 11 shows some key features of the company.

CupClub's financial status is currently in accelerator / incubator backed status. It has raised £450K from the pre-seed round on Feb 12, 2018 and £360K from the second pre-seed round on Feb 13, 2019.

CupClub is a winner of the Circular Design Challenge award at New Plastics Economy led by the Ellen MacArthur Foundation. CupClub is currently piloting their service in selected cafe retail stores in London and Palo Alto, CA. Additionally, CupClub is one of the limited numbers of focal firms that provided a comprehensive Life Cycle Assessment (LCA) report to review. With the LCA, we were able to evaluate the environmental benefits and understand how effective their model is consistent to the criteria in this tool.

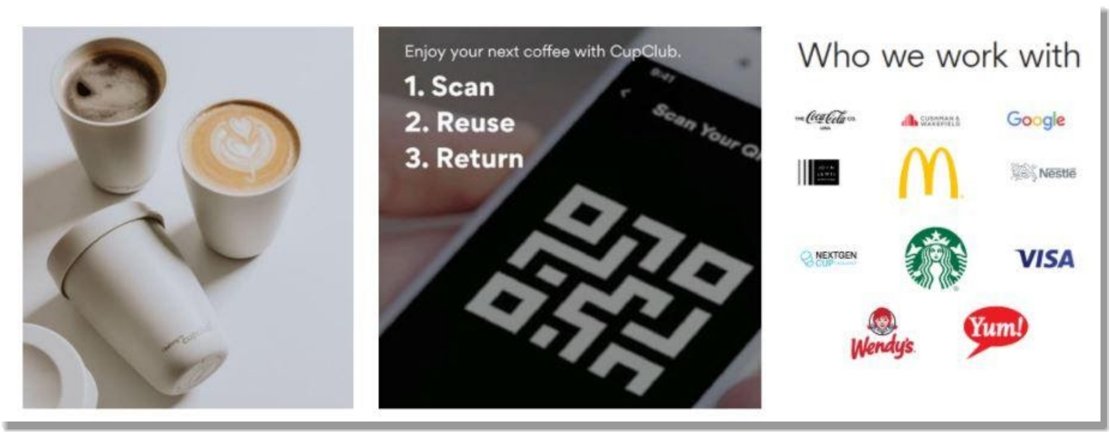

Figure 11. Early marketing of CupClub.

4.2 Key Information Gathering

After going through the public information on CupClub's official website and their LCA report, we gathered the following **basic information**:

- The 2018 Sustainability Report outlines a relatively comparative analysis of the environmental impacts of CupClub against alternative single use coffee cups and a reusable ceramic cup.

- The main benefit of CupClub is reducing plastic waste through single use cups, which are commonly made by Polyethylene terephthalate (PET), Polystyrene (PS), and Polypropylene (PP). The report shows that CupClub also has other benefits such as consuming less water and producing lower greenhouse gases as well as toxic gas emissions than comparable products (e.g., PLA recycled / compostable cup, EPS cup, ceramic cup, etc.).
- CupClub's cup uses an RFID system to track the individual cup use, which can give service companies useful data such as the consumption pattern of the customers. The typical cup consists of 49.3g of PP and the lid from 22.03g of LDPE.
- The software app. for CupClub is active and running. CupClub cups are free for customers but charge businesses at $0.25/drink sold for offering their cups as a service. It is still unclear if businesses will be incentivized to utilize this service since costs are coming from their bottom line.

Questions we have:

- Adoption and return rate:
    - No published results from pilots available yet (London and Palo Alto)
    - Unclear of adoption and usage rate, especially after onset of COVID-19

- Competition:
    - How does CupClub compare to the other NextGen Cup Challenge winners? (e.g., business model, environmental impacts and benefits, scalability, adoption rate, etc.)
- Market Demand:
    - Do businesses want to invest into CupClub as much as consumers want to use it for free?
    - Will businesses increase the cost of their drinks to cover the CupClub service fee, therefore burdening the consumer with the increased cost?
- Manufacturers / Suppliers:
    - It is still unclear who manufactures the cup and provides the washing service. The only available information is that within the U.S., they have partnered with selected Starbucks and McDonald's stores in Palo Alto, CA.

After gathering the background information and initial thoughts, we can use the tool to render further suggestions.

4.3 Evaluation with PRISET

4.3.1 Sustainability Aspects of Mission & Vision

There is no clear mission and vision statement on CupClub's website, but the following words could serve as their goals:

- "CupClub partners with businesses to make drinks-on-the-go more sustainable;

working together towards the ultimate goal of zero waste."

- "Each step of the CupClub journey is eco-friendly: from manufacturing, to cleaning, to transport using 50% less CO2 than single-use cups."

Guidance Criteria

- Does the mission and vision support significant prevention, removal and reduction of plastic waste from entering the environment?
  The company claims that its product is reusable and could make use of its drinks-on-the-go models to achieve zero waste in the end. Certainly, when making further analysis, evaluators need to accompany measurements in the potential scale section to fully understand the exact number of plastic waste reduction.

- Does the mission convey a purpose that contributes to advancing sustainability?
  The company indicates that each step of the process is eco-friendly, from manufacturing, cleaning, to transporting. Evaluators need analyze the data in the LCA section to fully understand the life cycle sustainability compared to traditional or typical single-use plastic cups.

- Are sustainability and social responsibility goals well-defined and measurable?

  The company says its product could have 50% less carbon dioxide emission, which is quite a strong and measurable indicator in the mission statement. According to Table 3 in this criterion, the company uses life cycle assessment to demonstrate their defined and measurable sustainability goal.

4.3.2 Circular Economy Approaches

According to the sustainability report, the cup is a recyclable (assumed 90% recyclable) petroleum product with RFID chips. Table 7 is a checklist of their list of the CE purpose, which is indicated as an example in our **Circular Economy Approaches** section. The "Pass" code means that the company's innovation basically passes the characteristic, and the "Verify" code means that this purpose should be furtherly checked and determine if it is applicable for the CupClub.

Table 7. Checklist of the circular economy purposes for plastic packaging

Elimination of unnecessary plastic packaging through redesign, innovation, and new delivery models is a priority	Pass
Reuse models are applied where relevant, reducing the need for single-use packaging	Pass
All plastic packaging is 100% reusable, recyclable, or compostable	Verify
All plastic packaging is reused, recycled, or composted in practice	Pass

The use of plastics is fully decoupled from the consumption of finite resources	Verify
All plastic packaging is free of hazardous chemicals, and the health, safety, and rights of all people involved are respected	Pass

Guidance Criteria

- How does the innovation reduce plastic use and/or plastic waste?
  The innovation mainly takes advantage of reusable cups with an RFID system to track the cups. Intuitively, the company could reduce plastic waste compared to single-use cups, but two parameters are significant to consider: the plastic content (i.e. the difference of unit plastic content and plastic type), and the service life (i.e. how many times the cup could be reused). It is difficult to directly quantify in this case, because the company's cup consists of PP and LDPE, but the comparable ones are paper cups with PE/PLA, EPS, and ceramic. Although the report shows a strong reduction of carbon dioxide equivalent emission, evaluators still need to know what are the most typical plastics that could be replaced.

- What is the end-of-life of materials used for the innovation?
  The report assumes different scenarios of the end-of-life situations for its product and other comparable ones. One of the typical scenarios is 90% recyclable, 5% landfill and 5% incineration. Also, it needs about 200km on average to transport to the recycler for the CupClub product. The company also assumes an average of 132 uses, wash, and drying before going to the end-of-life process. Although the environmental impacts are clearly listed, evaluators need to pay attention to the different consequences if the recyclable rate and service life change.

- Does the business plan use holistic, life cycle thinking to consider the upstream and downstream impact on the total quantity of plastics (virgin and recycle) wasted?
  The business uses the life cycle thinking to consider the GHG emission, water use, land use, toxicity, etc. in the whole upstream and downstream chain including the CupClub product and other comparable ones. More information could be discussed in the Life Cycle Assessment section. The question here is still related to our ultimate goal: how much plastic waste could be reduced when using a reuse scheme? Since after a certain service life of reusing, the cup will finally go through end-of-life treatment, has the company considered final recycling methods, and what are the practical ways to reduce energy consumption and emissions during the wash and transportation processes?

4.3.3 Potential Plastic Reduction Scale

Besides comparing the performance of CupClub with other competitors, we need to consider the extent to which a given innovation will scale within the broader economy to fully investigate the sustainability of CupClub's service.

CupClub has provided the material information of their reusable cups and compared them with their competitors. Table 8 is an example of their comparison. It is estimated that 50 billion disposable coffee cups are consumed in the US every year, and if all disposable cups are replaced with CupClub's product, 0.183 Mt of plastic can be reduced per year which accounts for around 0.3% of total US plastic consumption.

Table 8. Material comparison between CupClub and disposable coffee cup

Cupclub Cup		Single use coffe cup		Equivalent coffe cups (132 use)	
PP (g)	49.3	Paper (g)	10	Paper (g)	1830
LDPE(g)	22	PE (g)	1	PE (g)	554.4
Reuse time(s)	132	Corr.sleeve (g)	3.7	Corr.sleeve (g)	488.4
		PS-lid(g)	3.2	PS-lid(g)	422.4

4.3.4 Certifications

CupClub has not given any information about their certifications, but it doesn't mean that they are not qualified as a sustainable product because the product is still in development and practice. According to their sustainability report, it will be helpful if they can get following types of certifications:

- Business strategy - B Corp
- Energy Savings - Energy Star
- Environmental Management - ISO14000
- GHG Emission - Product Carbon Footprint Label, Science Based Targets Initiative, and Climate Neutral Certified
- Water Savings - WaterSense Certification
- Plastic Recycle - Post Consumer Resin (PCR), Mass Balance Certification, Recycled Claim Standard (RCS), and Global Recycled Standard (GRS)
- Quality assurance - Recycled plastic Component recognition

4.3.5 Life Cycle Assessment

CupClub has provided a LCA report which includes comparative analysis of the environmental impacts of CupClub against alternative disposable single use coffee cups and a reusable ceramic cup. As described in Life Cycle Assessment section, we'd like to ask following questions for CupClub:

- Was the LCA conducted by a reputable consultant or other LCA expert?
  Study conducted by Giraffe Innovation Ltd, which is one of the UK's top green businesses due to its extensive experience in delivery of a wide range of

sustainability driven projects.

- Was the LCA peer reviewed in accordance with ISO standards?
  A 3rd party peer review was conducted during July, 2018, which follows "[p]rocess intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" (ISO 14044:2006, section 3.45).

- Are the functional unit and system boundaries appropriate for product/system and comparisons?
  - System boundaries are clearly defined and appropriate (Figure 12), which follows "consecutive and interlinked stages […] from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1).
  - Functional units is sufficient, though somehow arbitrarily defined as 132 uses (expected useful life of CupClub cup), which follows "Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)

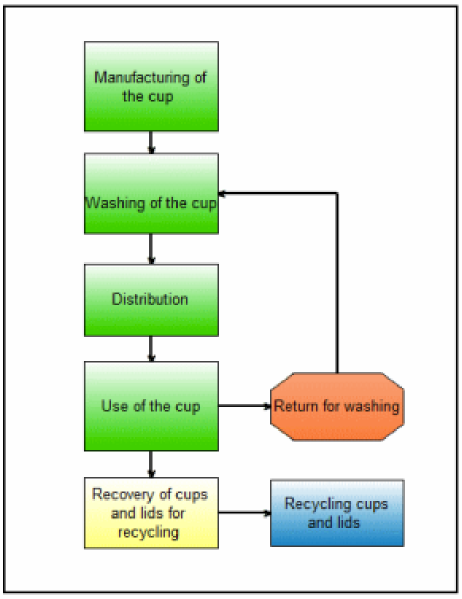

Figure 12. System Boundary of Cupclub's LCA[57].

- Has data quality been taken into consideration in interpreting results?
  To check data quality, the data quality indicators (Table 9) have been clearly defined in the report based on ISO 14044 Section 4.2.3.6.2. Each information is measured by these matrices and deemed sufficient. Although most data have been measured by the indicators, the conclusion and interpretation of the LCA report does not directly reflect how the data quality measurements affect the final results.

Table 9. Data quality indicators when checking the LCA report

Score	1 (Best)	2	3	4	5 (Worst)
Reliability of the source	Verified data based on measurement s	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Representative	Representativ e data from sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativ eness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

- Have sufficient uncertainty and sensitivity assessments been performed to consider an expected range of real-world situations?
  The report has analyzed the sensitivity and uncertainty regarding cup manufacture source, washing energy consumption, and transportation distance. The change of each kind of impact under these uncertainty or sensitivity scenarios have been estimated, but it could be more rigorous if they can include more scenarios.

4.3.6 Specific Technology Criteria

The service provided by CupClub is a typical reuse & refill innovation, and the collection process is improved by using an RFID system to track each cup. For this innovation, we need to consider both questions for reuse & refill innovations and the related tracking system.

- Will collection, return transportation, and cleaning of reusable packages increase the use of fossil energy or strain a water scarce region?

By comparing the equivalent consumption of different cups, the LCA establishes several break-even points for each kind of cup. According to their data, the cup can be used at least 132 times, which is higher than break-even points of all disposable cups, which means the supply chains are expected to have lower energy and water use than disposable cups.

- Does the new plastic or other non-plastic material used for the package have a robust recycle market or viable compost solution?
  The cup is made of LDPE and PP, which are commonly accepted by most recyclers as the source of post-consumer resin, and both have robust recycle markets.

- Will a heavier package pose problems upstream, downstream or in use?
  No. It does not appear that the CupClub cup is more difficult to fill and use.

- What is the break-even number of reuses where total energy use and GHG emissions are reduced versus a single use package/container?
  As shown in Figure 13, the breakeven number of reusing is 72 vs. paper/PS cups at 1% recycle rate and 132 at 80% recycle rate; 100 vs. EPS cup; and is better than ceramic until about 2000 uses.

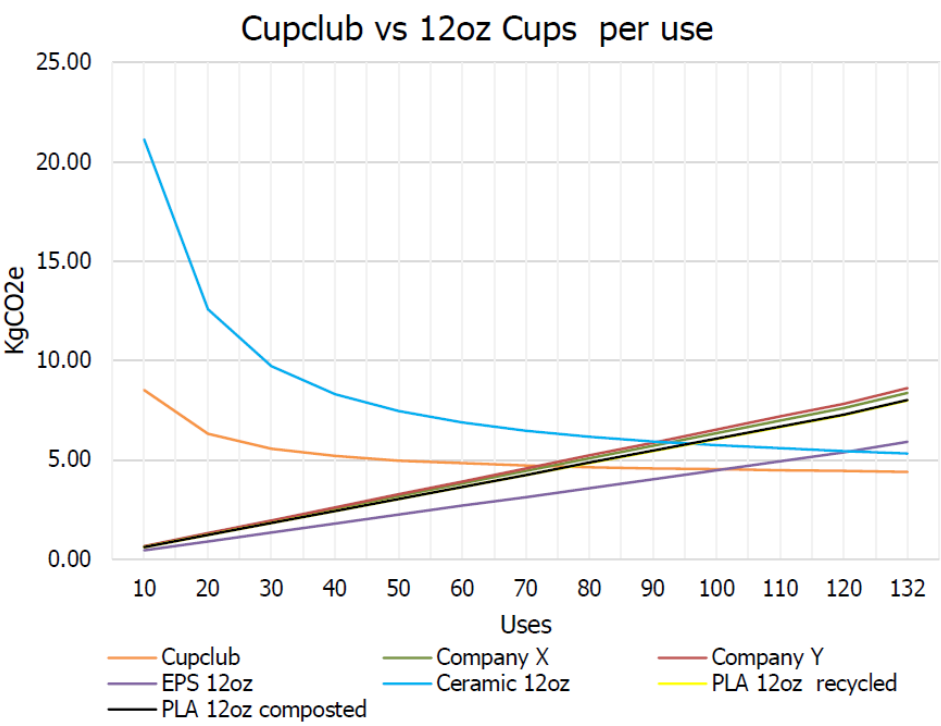

Figure 13. Emission comparison of CupClub and other 12oz cups[57].

4.4 Case Summary and Suggestions

CupClub's case has provided us an example of how to use our tool to evaluate an innovation. Although we cannot quantitatively figure out CupClub’s sustainability performance with a single case study, we can find how these criteria potentially affect our judgement. The first part is mission & vision, and Cupclub's mission & vision clearly contribute toward minimizing plastic waste from entering the environment. Mission & vision is important but it's a qualitative concept that is not so comparable among companies. For scale analysis, evaluators should compare innovations with each other by analyzing the scale of the plastic waste reduction with the same equivalent units. In CupClub's case, they converted the single use cup's data to an equivalent value of 132 uses to make the data comparable in their scenarios. Cupclub does not have any certification in current phase, and there can be some potential improvement in this section. For Circular economy and LCA, CupClub has integrated them into their sustainability report. It converts the competitors' parameters into same function units and equivalent quantities, and compares them under the same scenario, then interprets the result based on the breakeven point of the comparison. Cupclub has considered the uncertainties and sensitivities in their LCA report, but it lacks in depth analysis on the impact of uncertainties and sensitivities. Evaluators should acquire the information of uncertainties and sensitivity from the company if their LCA lacks consideration of these points.

In conclusion, we'd like to see the company meet our criteria as much as possible. If the company's current available information is not enough to answer these criteria, we should estimate when and how they can answer these critical questions and acquire information when it is necessary.

5. Conclusion

The team developed the **Plastic Waste Reduction Innovation Sustainability Evaluation Tool** to provide a framework and criteria to assess the sustainability performance of businesses seeking to commercialize and/or expand market penetration of waste reduction strategies and technologies. General guidance is presented for evaluating environmental sustainability of basic business models that focuses on the company's mission & vision, circular economy attributes, and potential scale of the waste reduction innovation. More in-depth tools for evaluating specific technology innovations include third party certifications and life cycle assessments that require more date to conduct. Waste reduction innovations were classified into four categories: reuse & refill, alternative materials, innovative design and recycling; and specific guidance criteria in the form of questions were presented to highlight key drivers of sustainability performance in each category.

Sustainability assessment is complex as it must consider existing incumbent processes and technologies and consider challenges in characterizes waste reduction strategies across technology readiness levels. **PRISET** is not a expert system that scores environmental sustainability performance of innovations. In contrast it should be treated as a resource and educational tool to provide supporting information and criteria for sustainability assessment on plastic waste reduction by vested parties (entrepreneurs, investors, consultants, etc.). Feedback from the assessment will also be useful for innovation companies themselves to focus efforts on those criteria they have not addressed.

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