Addressing the Limitations of Life Cycle Assessments for Circular Economy Packaging Innovations with the Kaiteki Innovation Framework

by

Andrew John De Los Santos

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved June 2020 by the
Graduate Supervisory Committee:

Tom Seager, Chair
Kevin Dooley
Rajesh Buch

ARIZONA STATE UNIVERSITY

August 2020

ABSTRACT

Historically, Life Cycle Assessments (LCA) guided companies to make better decisions to improve the environmental impacts of their products. However, as new Circular Economy (CE) tools emerge, the usefulness of LCA in assessing linear products grow more and more obsolete. Research Question: How do LCA-based tools account for reuse/multiple life cycles of products verses CE-based tools?

The Kaiteki Innovation Framework (KIF) was used to address the question of circularity of two packaging materials using an Environmental LCA to populate its 12 CE dimensions. Any gaps were evaluated with 2 LCA- based and 2 CE-based tools to see which could address the leftover CE dimensions.

Results showed that to complete the KIF template, LCA data required one of the LCA-based tools: Social Life Cycle Assessment (SLCA) and both CE-based tools: Circular Transition Indicators (CTI) and Material Circularity Indicator (MCI) to supplement gaps in the KIF. The LCA addressed 5 of the KIF dimensions: *Innovation Category Name, Description, GHG Impact, Other Environmental Impacts, and Value Chain Position*. 3 analytical tools addressed 5 more:: *Effect on Circularity, Social Impacts, Enabling Technologies, Tier 2 and 3 Requirements, and Value Chain Synergies.* None of the tools could address the KIF Dimensions: *State of Development or Scale Requirements*. All in all, the KIF required both LCA-based and CE-based tools to cover social and socio-economic impacts from a cradle-to-cradle perspective with multiple circular loops in mind. These results can help in the research and development of innovative, circular products that can lead to a more environmentally preferred future.

TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

CHAPTER Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1

BACKGROUND

Plastic Packaging History and Impacts

Plastics emerged during the Industrial Revolution between the 1800s and 1900s as a transformative product of human manufacturing that helped both people and the environment. Scientists engineered these synthetic materials to improve material properties (i.e. lightweight, flexible, and durable). Since the 1950s, plastics substituted natural materials such as wood, metal, leather, rubber, and ivory. The need to extract natural materials for items such as insulation, textiles, and furniture decreased as manufacturers started using plastic as a cheaper alternative that causes less harm to the environment (Lyons, 2019). Plastics became not only ubiquitous in everyday life but also infamous to the environment. Since the first Earth Day commenced across America in 1970, the sheer size of modern environmentalism brought attention to many topics, including the "wastefulness of a new affluent society" (Woodhouse, 2014). Later research reveals a linkage between chemical compounds (i.e. bisphenol A) in plastics and human health and reproduction (North, 2013).

The design of plastics favored functionality, but not recyclability (Bellis, 2019). Experts predict the same plastics developed during the Industrial Revolution to double over the next 20 years, with plastic packaging representing the largest portion of the total volume. As plastic pollution increases, the usefulness of the function of them decreases. After the first use, plastics lose 95% of their material value ($80-120 billion annually) due to processing and poor collection and human/technical challenges. Even if plastics do get collected, only 2% undergo closed-loop recycling, which retains material quality by cycling materials into the same applications. Therefore, most plastics do not get recycled and about a third of plastics produced leak into the environment ("The New Plastics Economy*,"* 2016).

By 2050, the number of plastics in the oceans may outweigh fish, which raises concerns for both the environment and human health (*The New Plastics Economy*, 2016). 84% of ocean plastics contained at least one Persistent Bio-accumulative Toxic (PBT) chemical, which marine life might mistake for food and consume. This bioaccumulation of chemicals can pass up the food chain, threatening the health of humans that feed on marine life. Additionally, plastics can impact the economy. The environmental damages cost about $13 billion a year due to waste cleanups and financial losses by fisheries (*The Price Tag of Plastic Pollution*, 2019). Single-use plastic packaging, specifically from CPG companies, represents a global sustainability issue that impacts the environment, economy, and society. Ultimately, researchers suggest that businesses should seek out more sustainable alternatives to packaging (Ward et al., 2019). Due to the ubiquitous use of plastic packaging in everyday life and its environmental and socio-economic impacts, I decided to look for LCA's on those products for the KIF analysis.

The Circular Economy (CE)

As the growing population depletes finite resources faster than Earth can replenish, companies need new economic models like CE to "decouple economic growth and development from the consumption of finite resources" (*Circularity Indicators*, 2015). The concept of CE has been framed by the Ellen MacArthur Foundation (EMF), a charity that works with business, government, and academia. This organization created 7 major schools of thought summarized in **Table 1** below (Plus an additional). According to the EMF, the schools of thought have been integrating into mainstream conversations with industries, academics, and policymakers that want a vision of a restorative and regenerative economy by design (*Towards the Circular Economy, Vol. 1*. (2013). Below are the descriptions for each of EMF's Schools of Thought and how they can inspire new innovations.

Table 1

The 8 Major Schools of Thought in the Circular Economy

Name of School	Description
Cradle to Cradle	Eliminate waste, use renewable energy
Performance Ecology	Extend Product-life, recondition activities, and prevent Waste
Biomimicry	Emulate nature as a model, be a measure to judge sustainability, learn instead of extract
Industrial Ecology	Focus on closed-loop system processes without undesirable by-products
Natural Capitalism	Increase productivity and restore/regenerate natural resources, provide a continuous flow of services
Blue Economy	Focus on the global south and base solutions on the environment and physiological traits
Regenerative Design	Design out waste and pollution, keep products and materials in use, and regenerate natural systems.
Thermodynamic Theory of CE	Products disposed to environmental sinks generate high entropy, and knowledge of the entire system is lost.

1st Major School of Thought in CE: Cradle to Cradle

Chemist McDonough and architect Braungart define Cradle to Cradle as both a framework and a certification process. The Cradle to Cradle framework defines all material inputs and outputs as either technical or biological nutrients so waste from one system is used as a resource for another. The design principles are inspired by natural systems: (1) Everything is a resource for something else, (2) Use renewable energy, (3) celebrate diversity (Braungart, & McDonough, 2009). From these principles emerged a globally recognized certification process to turn the philosophy into actionable results. Companies can compile supply chain data, develop optimization strategies, and submit an assessment report to certify their product and add it to the Cradle to Cradle product registry. Cradle to Cradle inspires innovations that can meet the categories below (*How to Certify):*

5 Cradle to Cradle Certified™ Assessment Categories (*Cradle to Cradle Certified, 2016*):

- **Material Health** (chemical composition)
- **Material Reutilization** (design for technical or biological cycles)
- **Renewable Energy and Carbon Management** (renewable sources for electricity and offsets)
- **Water Stewardship** (managing product-relevant effluent)
- **Social Fairness** (human rights and positive impact strategies)

2nd Major School of Thought in CE: Performance Economy

The Performance Economy, an economic model created by architect Walter Stahel, includes four main goals: product-life extension, long-life goods, reconditioning activities, and waste prevention. The performance economy invokes the product-as-service business model for manufacturers to take ownership of the product through renting or leasing. The Performance Economy inspires innovative products for minimal maintenance, quick disassembly, and easy reusability.

In terms of measurement, The Performance Economy uses 2 main metrics for economic sustainable productivity (Stahel, 2010):

- **Value-per-weight (EUR/kg)-** Wealth and growth of goods flourish with minimal resource consumption
- **Labor-per-weight (mh/kg)-** Man-hours (labor) per weight of activities; Local skilled jobs with minimal non-renewable resource consumption.

3rd Major School of Thought in CE: Biomimicry

Biologist Janine Benyus defines Biomimicry as a discipline that mimics biological processes as part of the design process for materials. In her book, she describes three levels of biomimicry. The first level of biomimicry: Mimic the natural form (i.e. how an owl's feather mechanics can inspire fabric that opens along its surface). The second level of biomimicry: Mimic the natural processes (i.e. how self-regulating feathers can inspire green chemistry without toxins). The third level of biomimicry: Mimic the natural ecosystems (i.e. how an owl in a sustaining biosphere can inspire ethical labor for fabric-making and transportation using renewable energy). (Benyus, 2002). Biomimicry inspires innovations that incorporate nature into the design process.

The framework includes 6 life principles for ecological and sustainable design (Peters & Peters, 2011):

- Evolve to survive
- Be resource-efficient
- Adapt to changing conditions
- Integrate development with growth
- Be locally attuned and responsive
- Use life-friendly chemistry

4th Major School of Thought in CE: Industrial Ecology

Engineers Graedel and Allenby define Industrial Ecology as the study of industrial and economic systems and their linkages with complex integrated human/natural systems. The study focuses on the flow of energy and materials of products in industrial systems. Some data visualization tools used include Sankey diagrams, process energy use diagrams, and bar clustered diagrams to show different energy sources, energy per mass for production, and side-by-side energy consumption at different lifecycle stages, respectively (Graedel & Allenby, 2010). Industrial Ecology inspires innovative industrial products that uses efficiency to reduce resource use and waste outputs.

9 main measurement categories comprise the "National Material Metrics for Industrial Ecology" (Zapico et al, 2010):

- **Total per Capita Inputs**
- **Input Composition**
- **Input Intensities**
- **Recycling Indices**
- **Output Intensities**
- **Leak Indices**
- **Environmental Trade Index**
- **Mining Efficiency**

5th Major School of Thought in CE: Natural Capitalism

Environmentalists Hawkins and Lovins define Natural Capitalism as a global economy model where business and environmental practices operate in synergy for interdependence between human-made capital and flows of natural capital. Natural Capitalism allows commercial enterprises and communities to operate efficiently while maintaining nature's life support systems. Natural Capitalism inspires innovations that regenerates natural systems while simultaneously improving the economic system. It includes 4 principles (Hawken et al., 1999):

- Radically increase the productivity of natural resources
- The shift of biologically inspired production models and materials
- Move to a service-and-flow business model
- Reinvest in the natural capital.

6th Major School of Thought in CE: Blue Economy

Businessman Pauli defines the Blue Economy as an economy that shifts society from scarcity to abundance with locally available resources. It embodies an open-source platform that introduces 100+ global scientific innovations inspired by nature that can create millions of jobs. The Blue Economy includes 21 founding principles (i.e. natural systems cascade nutrients, matter, and energy) (Pauli, 2015). It inspires innovations that can be made at high-quality at lower costs to save on resources.

7th Major School of Thought in CE: Regenerative Design

Regenerative Design, a process-oriented system theory coined by Professor John T. Lyle, describes processes that use systems thinking to create resilient systems to meet societal needs while maintaining nature's integrity. It aims to develop restorative systems not only for humans but for other species and generations (Lyle, 1994). Lyle's book, *Regenerative Design for Sustainable Development*, does well to explain the theory and create the knowledge base of regenerative design. It strives to inspire innovations that can benefit not only current generations but also future ones to come without degrading planetary resources.

8th Major School of Thought in CE: The Thermodynamic Theory of CE

Although this theory is not one of EMF's 7, it is important to include. Products eventually degrade, wear out, and break apart. This environmental pollution increases entropy, defined as the measure of the state of the world that increases after every spontaneous change, and whenever exergy (useful energy) is consumed (Ayres, 2016).

Decreasing the entropy of products through effective recycling utilization of resources can help compensate for the inevitable increase of entropy in the environment. When products are created, they extract low-entropy resources and create high-entropy resources. Ayres stated that although global economic growth results in degradation of planetary resources, human knowledge (what we know about the system) can lead to creative innovations for optimizing and controlling “exergy flows and material transformations in addition to social activities and institutions” (2016).

CE strives to reduce entropy gains through technological advances for greater efficiencies within the supply chain and ultimately absorbing the high-entropy waste by reusing, remanufacturing, or recycling the product at the end of its life. According to Dr. Seager, when products are disposed to environmental sinks such as to the environment or the landfill, it generates high entropy, and knowledge of the entire system (extraction → use) is lost. In this Thermodynamic Theory of CE, technical cycles can help keep that knowledge and reduce entropy gains.

Reusing materials captures the knowledge value of the entire system since it requires no reprocessing of materials; simply the transfer of ownership (i.e. second-hand smartphone). Remanufacturing materials capture the knowledge value of the material and component, but not the entire system since the product requires new parts to return to its original condition (i.e. remanufactured office chair that had a broken arm). Recycling materials capture only the knowledge value of the materials since the system becomes deconstructed for materials to convert back into raw materials that might become an entirely new system (i.e. plastic water bottle). CE should aim to cycle materials back into the supply chain to capture the most knowledge value of the original system while keeping entropy (i.e. environmental impacts) at its lowest. The figure below by Dr. Seager illustrates his Thermodynamic Theory of CE:

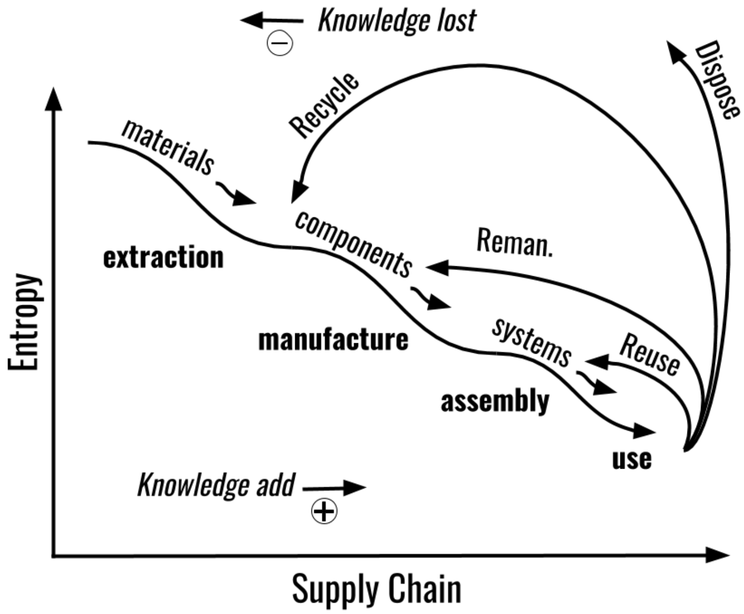


Figure 1: The Thermodynamic Theory of CE by Dr. Seager

Analysis of the 8 Major Schools of Thought

The major schools of thought listed above represent different frameworks that approach CE in unique ways. Although only a few offer metrics for metrics for measuring the circularity impacts (Cradle to Cradle, Performance Ecology, and Industrial Ecology), the list is meant to inspire different ways products can be innovated to move society towards a more circular economy. Product designers can take inspiration from 1 or multiple Schools of Thought when thinking of questions to consider for circularity.

The Trend Towards CE Solutions

Although plastics have plagued our environment, the demand towards more sustainable solutions increases. Globally, the number of consumers who say they would be willing to pay more for sustainable or eco-friendly products has grown from 47% to 59% in seven years ("Sustainable Packaging Unwrapped", 2019). Companies need to look past materials created without intent for recycling (i.e. petroleum-based materials) and look for new materials that can easily re-enter technical or biological cycles and transform the way they make, use, and remake products. CE frameworks and analytical tools support the movement for more sustainable materials. I will analyze and compare a small handful of them.

Kaiteki Innovation Framework (KIF)

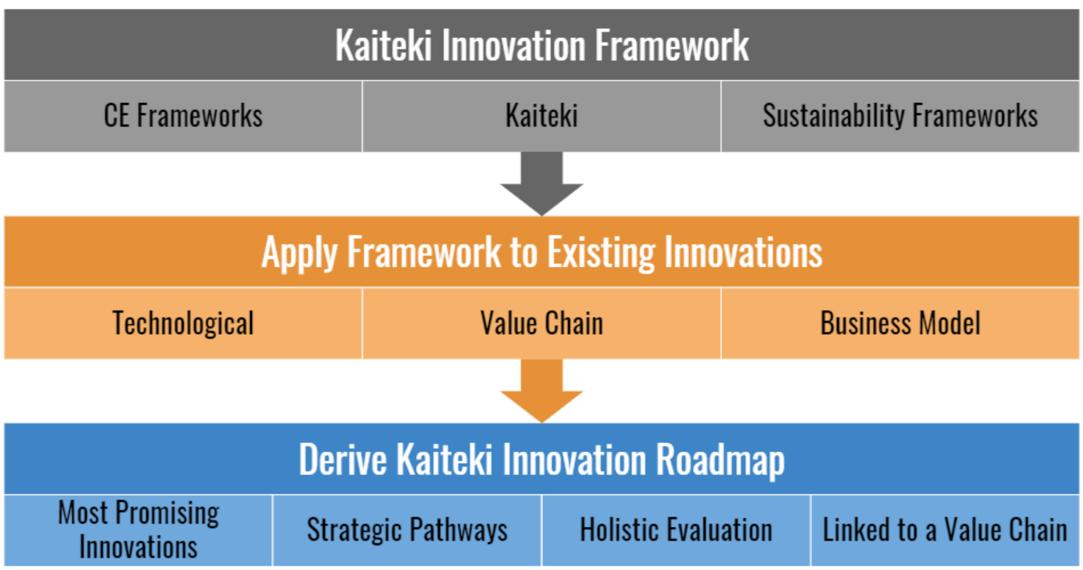


Figure 2: Developing the Kaiteki Innovation Roadmap

Shown in the figure above, the KIF uses concepts of CE, Sustainability, and Kaiteki (the sustainable well-being of people, society, and our planet earth) to assess existing innovations in a plastics supply chain to derive a roadmap for strategic decision-making of new materials. Created by academics at Arizona State University, the KIF qualitatively assesses the existing value chain of packaging material and identifies the impacts or potential tradeoffs. The KIF assesses each innovation subcategory to reveal current and future states. Ultimately, the KIF's assessments of the innovations will show the risks and opportunities that plastic industries will face depending on decisions along the supply chain.

Mitsubishi Chemical Holdings Company (MCHC), a plastics chemical company that manages a full range of plastic products, plans to use the KIF to holistically assess circular economy innovations in their plastic value chain across many dimensions of CE and guide them on a roadmap. The KIF provides an inventory of qualitative assessments based on literature to understand the impacts and potential trade-offs for a more environmentally preferred future. Therefore, this case study can support the use of KIF and identify other supplemental CE-based that can complete the template below:

Table 2

The KIF Template (Dimensions and Descriptions)

Dimension	Description
Innovation category name	Title
Description	Brief summary of what innovations in the category do
State of development	Categorical (E.g. lab-only, early development, etc.) (cite the month & year)

Effect on circularity	(Quantitative) Description of how innovation impacts circularity (i.e. flows thru value chain)
GHG impact	Relative impact on life cycle GHG impact (include Scope 3)
Other environmental impacts	Relative impacts on other environmental dimensions (use tier categories)
Social impacts	Relative impacts on social dimensions (use tier categories)
Enabling technologies	Component technologies that drive cost and performance of innovations in category
Tier 2 and 3 requirements	Practices that must be present for innovation in category to be considered Tier 2 or 3 in sustainable strategy framework
Value chain position	Primary value chain position for deployed innovation
Scale requirements	Whether innovation can be adopted by all or only large organizations
Value chain synergies	Other value chain nodes that enable or are enabled by innovation

Life Cycle Analysis (LCA)

One of the most historical and popular assessment tools, the Life Cycle Analysis (LCA), uses software to addresses the potential environmental impacts throughout the life cycle of a product to support decision-making and highlight opportunities for efficiency across a value chain. LCAs can help optimize investments in research and development and provide support for environmental claims. According to the International Organization for Standardization (ISO) 14040 and 14044 standards published in 2006, LCAs include four main phases:

- **Goal and Scope** – defines the intended use of the LCA and creates a boundary for the system
- **Inventory Analysis-** collects input and output data, including resources and emissions

- **Impact Assessment –** translates inventory data into indicators of potential impacts on natural resources, human health, and the environment
- **Interpretation-** interprets the results and undergo a sensitivity and uncertainty analysis

Scientific papers highlighted gaps in LCA concerning CE analysis. For example, in a publication by Niero and Hauschild, they examined different combinations of frameworks: Cradle-to-Cradle (C2C) Material Circularity Indicator (MCI), and Life Cycle Analysis Sustainability Assessment (LCSA) on a case study on aluminum cans. The authors recognized that combining different assessment tools in conjunction with LCA can provide better CE analysis. They concluded that the LCSA would be the best fit to evaluate circularity strategies since it includes LCA, Environmental Life Cycle Costing, and Social LCA (Niero et al. 2017). Of the CE Schools of thought, they used a combination of three: Cradle to Cradle, Performance Ecology, and Industrial Ecology.

The authors defined CE as an objective to maximize the value and utility of materials. This definition involves concepts that include eliminating waste, extending product-life, and avoiding undesirable by-products. This provides an example of how LCA might require supplemental analytical tools in CE to capture other impacts and scopes normally excluded in traditional LCAs, and that different combination of tools yield different findings in terms of social, environmental, and economic impacts. The KIF represents one of many CE-based frameworks that may bridge the circularity gap between stand-along LCAs and wholistic CE assessments.

CHAPTER 2

METHODOLOGY

Literature Review

I conducted a literature review identifying 25+ published LCA studies that compared a material with a linear life cycle (take, make, use, dispose) versus one with a circular life cycle (take, make, use, reuse, remake, etc.) Sources of information:

- International Journal of LCA
- Springer
- Science Direct
- Waste & Resource Action Programme (WRAP)

Publications Selection Criteria

Of the 25+ studies, a list of selection criteria guided the selection of suitable publications for analysis. This ensures the robustness and scientific credibility of the studies.

<u>My criteria for publication selection:</u>

- The study analyzed packaging material for food or beverages
- The study followed standardization using ISO 14040- LCA Principles and Framework and the ISO 14044- LCA Requirements and Guidelines

- The study compared at least two end-of-life options for the materials, so they have the same functional unit, system boundary, etc.
- The study originated from a scientific journal
- The study included primary research, not based on analysis, or interpreted information from another study.
- The study had feasible recommendations for end-of-life scenarios of the material given its geographic location
- The study used transparent assumptions with clear key parameters to identify how one study differs in conclusion from a similar one.
- The study provides adequate references to gather additional data from

<u>The LCA selected:</u>

Humbert et al. (2009)- LCA of two Nestlé baby food packaging: glass jars (circular) vs. plastic Polypropylene (Plastic #5) PP pots

<u>KIF as a Case Study:</u>

The KIF will provide an analysis of both the plastic pots and the glass jar from the LCA. Data from the LCA will mainly populate the 12 CE dimensions of the KIF. External sources will populate any gaps not addressed. I predict that the LCA will cover some, but not all of the KIF dimensions. Therefore, I will use 4 different analytical tools (2 CE-Based, 2 LCA-Based) to address any leftover KIF dimensions and compare their circularity analyses with that of the KIF and LCA.

Comparing the KIF to Other CE-Based and LCA-Based Tools

2 CE-based tools and 2 LCA-based tools will try to address the KIF dimensions not covered by data from the LCA. This is to understand which combination of tools could provide a more wholistic KIF analysis.

CE-Based Tools:

1. World Business Council for Sustainable Development (WBCSD)- Circular Transition Indicators (CTI)
2. Ellen MacArthur Foundation (EMF)- Material Circularity Indicator (MCI)

LCA-Based Tools:

3. US Environmental Protection Agency (EPA)- Sustainable Materials Management (SMM) Prioritization Tools
4. Social Life Cycle Assessments (SLCA)

Taxonomy of Circularity Indicators

To evaluate the 4 analytical tools above, I looked at a taxonomy developed for circularity indicators (C-indicators). In 2018, researchers developed the first taxonomy of 55 C-indicators to support a wide range of needs and requirements by practitioners, decision-makers, and policymakers. The proposed taxonomy aims to guide future research on C-indicators and implementation of CE from the micro to the macro-level (Saidani et al., 2019). The 10 categories are listed below:

1. **Implementation Levels** (*Systemic levels of CE implementation*)
    a. **Micro-level**- local level: organization, products, and consumers
    b. **Meso-level**- regional level: symbiosis association and industrial parks
    c. **Macro-level**- national level: city, province, region, or country
2. **Circularity Loops** (*Feedback loops for technical materials. They are listed below from the processes that capture the most material value to those that capture the least*)
    a. **Maintain/Prolong -** designing longer-lasting products for durability, maintenance, and repair
    b. **Reuse/Redistribute-** redistributing products and materials to new users in their original form (as close as possible) using marketplaces likes eBay
    c. **Remanufacture/Refurbish**
        i. **Remanufacture-** product is disassembled to its components and rebuilt (swapping old components) to as-new condition
        ii. **Refurbish-** product is repaired without disassembly or component replacement
    d. **Recycle-** Reducing a product to its basic materials to be remade into new products
3. **Performance** (*Circularity performance for monitoring progress*)
    a. **Intrinsic Performance-** focuses on the transition: resource efficiency and material consumption

b. **Consequential Performance-** focuses on the effects: environmental impacts and added value of products

4. **Perspective of Circularity** (*actual, potential*)

    a. **Actual Circularity**- The retrospective temporal focus of a CE transition

    b. **Potential Circularity**- The prospective temporal focus of a CE transition

5. **Usages** *(these are the potential usages of a C-indicator)*

    a. **Information purposes**- understanding the baseline, progress, and areas to improve

    b. **Decision-making purposes**- taking action (i.e. strategies, policies)

    c. **Communication**- for both the stakeholders and the public

    d. **Learning-** educating product developers and increasing awareness among consumers

6. **Transverality** *(the type of sector: general, sector-specific)*

    a. **General**- applied to any type of company regardless of size, location, industry, etc.

    b. **Sector-specific-** applied to a specific sector (i.e. building management)

7. **Dimension** *(degree of intelligibility or simplicity of C-indicators)*

    a. **Single Dimension**- light assessment useful for a managerial decision maker

    b. **Multiple Dimensions**- deeper assessment useful for experts, designers, or engineers

8. **Units** (*These indicator units can use a quantitative and/or qualitative approach to convey information*)
    a. **Qualitative Units-** Non-specific units focused on the process of CE implementation (inductive) (i.e. principles, pathways)
    b. **Quantitative Units-** Specific units focused on the numbers and calculations for computation (deductive) (i.e. %, $, kg, CO2, ratio)
9. **Format** *(These are manual and computational tools)*
    a. **Web-based tool**
    b. **Excel**
    c. **Formulas**
10. **Sources** *(These are the origins of C-indicators)*
    a. **Academics-** Scholarly papers published by universities
    b. **Industrial Companies-** Can include governmental and environmental companies
    c. **Consulting Agencies-** Private entities

Each of the 4 analytical tools will be categorized using the 10 categories of the taxonomy. This will help reveal the differences between each tool and identify which of the remaining KIF dimensions each tool could address if implemented.

Analyzing a Comparative LCA of Plastic vs Glass

Nestlé issued a comparative LCA in 2007 between two of their products for baby food packaging: a glass jar and a plastic pot in France, Spain, and Germany.

- **Purpose**: Assess the life cycle environmental impacts to inform the public of the differences between the two products.
- **System Boundary:** A cradle-to-grave analysis evaluated impacts from resource extraction to end-of-life.
- **Data Collection:** Inventory analysis originated from the IMPACT 2002+ and CML 2001 Midpoint Methods. Data was used from Nestlé, its suppliers, scientific literature, and databases.
- **Results:** Glass had lesser environmental benefits over the plastic pot due to factors such as plastic's production, weight, and transportation. Nestlé advertises that plastics have a 25% reduction in C02 emissions and energy consumption compared to glass (mainly due to production and transportation). The main impacts with the largest differences included energy reduction, global warming, respiratory inorganics, and terrestrial acidification/nutrification (Humbert et al. 2009). If the purpose of the LCA included principles of circularity to determine the more environmentally preferred product, then using other analytical tools as a supplementary analysis to the LCA might have led to a different outcome than plastics being preferred over glass.

KIF Analysis 1: Glass Jar (Circular Product)

For each of the products (plastic pot and glass jar), I assessed the LCA by Humbert et al. using the KIF to address each of the 12 CE dimensions. The KIF template was populated by data from the LCA, supplemented by external sources (i.e. news articles, industry reports). Each of the 12 dimensions was described in detail.

Table 3

The KIF Template (Analysis 1: Glass Jar)

Dimension	Description
Innovation category name	Nestlé Glass Baby Food Jar 200-g
Description	The innovation includes a white glass jar, paper label, PVC layer, Steel cap. Functional unit: provide a proper vehicle for a child's baby food meal in France, Spain, and Germany in 2007
State of development	Developed and commercialized
Effect on circularity	Glass jars have a recycling rate of 62% as primary glass raw material to create more glass cutlets. This avoids burden of production materials (sand, soda, dolomite, limestone).
GHG impact	Compared to the plastic pot, the glass jar has increased impacts: 13% more for primary energy, 3% more for global warming, 3% more for terrestrial acidification/nutrification
Other environmental impacts	Carcinogens, Terrestrial Ecotoxicity, Aquatic Ecotoxicity, Photochemical Oxidation, Non-carcinogens, Respiratory Inorganics, Ionizing Radiation, Ozone Layer Depletion, Land Occupation, Aquatic Acidification, Aquatic Eutrophication, Mineral Extraction
Social impacts	Health and safety, socio-economic repercussion, human rights, development of country
Enabling technologies	Glass Manufacturing: Batch House, Glass Furnace Operations, Forming Process
Tier 2 and 3 requirements	TIER 2 REQUIREMENTS: • Supply web and life cycle

	• Growth, profit, optimal efficiency • Classic plus life cycle perspective • Business management and resource management • Classic plus LCA, WRI CO2 EMS, DFE, GRI, E-Goals, LEED
Value chain position	Use-phase
Scale requirements	Small or large companies can purchase bulk glass containers from a manufacturer. Scaling up operations can include building a glass manufacturing plant (~$150 million)
Value chain synergies	End-of-life recycling: Glass Recycling Technology: glass breaker (metal discs) to break the glass and minimize contaminants (i.e. fiber and plastics), magnets and eddy currents to separate metal, furnace to melt glass, and molds to form new containers.

1. KIF Dimension: Innovation Category Name

Innovation category name	Nestlé Glass Baby Food Jar 200-g

The **"Innovation category name"** dimension refers to the material for the analysis: a 200-g glass baby food jar provided by Nestlé.

2. KIF Dimension: Description

Description	The innovation includes a white glass jar, paper label, PVC layer, Steel cap. Functional unit: provide a proper vehicle for a child's baby food meal in France, Spain, and Germany in 2007

The **"Description"** dimension refers to components of the "innovation": the glass jar as described by its functional unit in the LCA: provide a proper vehicle for a child's baby food meal in France, Spain, and Germany in 2007 (Humbert et al., 2009)

3. KIF Dimension: State of Development

State of development	Developed and commercialized

The **"State of development"** dimension refers to the product development stage (i.e. lab-only, early development). Although the LCA was conducted on popular Nestlé products that are globally sold and available in stores, more detailed product information is required to fully complete this dimension. Therefore, external sources on product development revealed that the glass jar falls under “developed and commercialized.”

Based on the product label shown on the figure in Humbert et al.’s LCA (See figure below), the glass pot, referred to the German baby food brand, Alete, was acquired by Nestlé from 1971-2014 (*Products from Alete*). They sold baby food in small, glass jars and still sell the same jars throughout Europe today in 2020. Although Alete has been acquired by different companies, they keep their production the same since it "remains solely under the owner” (*DMK Group acquires German-based baby food brand Alete*, 2019). Therefore, I assumed that for the “State of Development” KIF dimension, the glass jars fall under “developed and commercialized”. This can lead to more circular solutions since a closed-loop waste management strategy could be implemented at scale to capture the jars to clean and reuse, such as reuse drop-off locations near the grocery store chains that sell the products.

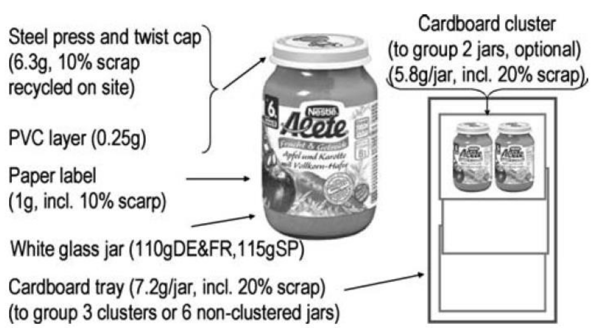


Figure 3: Glass Jar Components. Source: (Humbert et al. 2009)

4. KIF Dimension: Effect on Circularity

Effect on circularity	Glass jars have a recycling rate of 62% as primary glass raw material to create more glass cutlets. This avoids burden of production materials (sand, soda, dolomite, limestone).

The **"Effect on circularity"** dimension refers to how the innovation impacts circularity through its value chain. Although the LCA provided percentages on end-of-life scenarios, it lacked information on how the glass is reused into other technical cycles. Additionally, some of the waste management data were unsupported by clear sources. External sources on glass waste management data covered this dimension.

According to Humbert et al.'s LCA on end-of-life analysis, the glass jars have a landfill/incineration rate of 38% and a recycling rate of 62% (See figure below). Humbert et al. sourced their data from "national [waste management] practices" of France (2009). However, the year and source of that data used in the LCA remain unknown. Nationally in France, there is not a source for the number of glass containers recycled in 2007, although France reported a 33% recycling rate of general municipal solid waste (including glass containers) (*Municipal Waste Management in France*, 2013). Therefore, LCA data lacks transparency and credibility to accurately prove the recycling rate of 62% or what materials those recycled materials became.

The LCA provided glass recycling rates for Germany (86%) and Spain (51%) (See figure below). It is unclear why the LCA selected recycling rates from France (62%) as opposed to the other countries in scope with higher rates. Only Germany and Spain own factories to produce glass jars, not France. Additionally, Germany and France received more units of glass jars than France (Humbert et al., 2009). Lastly, there lacked information on how France recycled the glass and incorporated the material into new products.

High glass recycling rates can support circular technologies for capturing waste glass and incorporating more recycled content for the glass jars. The recycled glass can also act as a substitute in other materials. For example, a 2018 LCA showed that using glass powder from the mixed waste glass as an alternative cementitious material in concrete significantly lowers the environmental burden than the traditional concrete production model (Deschamps et al., 2018).

5. KIF Dimension: GHG Impacts

GHG impact	Compared to the plastic pot, the glass jar has increased impacts: 13% more for primary energy, 3% more for global warming, 3% more for terrestrial acidification/nutrification

The **"GHG impacts"** dimension refers to the greenhouse gas (GHG) environmental impacts. Humbert et al.'s LCA did well to address this dimension. Greenhouse gases include Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), and Fluorinated gases. According to the EPA, each gas affects climate changed based on three main factors (*Overview of Greenhouse Gases)*:

- How much is in the atmosphere?
- How long do they stay in the atmosphere?
- How strongly do they impact the atmosphere?

For the LCA, the justification for claiming the plastic pot more environmentally friendly than the glass jar came from the main differences in GHG impacts. Three main LCA indicators represented GHG impacts: primary energy, global warming, and terrestrial acidification/nutrification.

6. KIF Dimension: Other Environmental Impacts

Other environmental impacts	Carcinogens, Terrestrial Ecotoxicity, Aquatic Ecotoxicity, Photochemical Oxidation, Non-carcinogens, Respiratory Inorganics, Ionizing Radiation, Ozone Layer Depletion, Land Occupation, Aquatic Acidification, Aquatic Eutrophication, Mineral Extraction

The **"Other environmental impacts"** dimension refers to impacts other than greenhouse gas impacts on affecting the environment. 12 LCA indicators fall under this dimension (Carcinogens, Terrestrial Ecotoxicity, Aquatic Ecotoxicity, Photochemical Oxidation, Non-carcinogens, Respiratory Inorganics, Ionizing Radiation, Ozone Layer Depletion, Land Occupation, Aquatic Acidification, Aquatic Eutrophication, Mineral Extraction). 3 of these indicators fall into the category of "human health", or "social impact": Carcinogens, Non-carcinogens, Ionizing Radiation. However, they lacked social impacts on other stakeholders (i.e. human rights of workers), so they were left as "other environmental impacts."

7. KIF Dimension: Social Impacts

Social impacts	Health and safety, socio-economic repercussion, human rights, development of country

The **"Social impacts"** dimension refers to impacts on the lives of people involved (Umair et al., 2015). Although the LCA included some indicators that have social impact implications, they ultimately do not cover enough social impact categories to have their classification. External sources on social impact categories on the informal recycling sector for glass-covered this dimension.

The informal recyclers in France, known as "biffins", or "gleaners", collect, repair, and recycle waste, but suffer from judicial and police repression (*The Association of AMELIOR*). Therefore, to understand potential social impacts I looked at a Social LCA of the informal E-waste recycling sector in Pakistan. According to the 2015 Social LCA, workers are subject to crude processes that involve hazardous substances that affect human health and the environment. Stakeholder categories include workers, local community, society, and value chain actors. Potential Impacts include health & safety, socio-economic repercussion, human rights, and development of country (Umair et al., 2015). Therefore, by using the Social LCA impacts for e-waste recycling in Pakistan, I assume the same social impacts for glass recycling in France:

- **Health and Safety** (i.e. exposing workers to a toxic work environment)
- **Socio-economic repercussion** (i.e. lack of social security to cover the health expenses of workers)
- **Human Rights** (i.e. child labor that deprives children of formal education).
- **Development of Country** (i.e. lack of community engagement from business owners and workers in improving the community)

8. KIF Dimension: Enabling Technologies

Enabling technologies	Glass Manufacturing: Batch House, Glass Furnace Operations, Forming Process

The **"Enabling technologies"** refers to the technology that drives the cost and performance of the innovation. For a glass jar, that technology describes the glass manufacturing process. The LCA, however, does not describe the process of how the products were made, only the impacts from those processes. Therefore, external sources on glass manufacturing covered this dimension.

The glass manufacturing industry has 3 main steps to produce glass (*Glass Manufacturing, Glass Containers Manufacturing Process*):

1. Batch House
    a. Workers inspect, proportion, weight, and house raw materials (i.e. sand, soda ash, limestone, cullet) in large storage silos.
    b. Workers mix the raw materials with recycled glass cullet
    c. The mixed material travels on a conveyor belt or monorail train and enters a furnace
2. Glass Furnace Operations
    a. The mixture passes through the melter at about 2800F and gets cooled at the refiner that acts as a holding basin.
3. Forming Process
    a. From the refiner, glass flows using gravity through the feeder to cool the material and have a uniform viscosity. Machines shear off falling globs (lumps) of molten glass that fall into chutes and then

enter an I.S. Machine, "Individual Section II Machine" to form the molten glass using blow molds into containers.

9. KIF Dimension: Tier 2 and 3 Requirements

Tier 2 and 3 requirements	TIER 2 REQUIREMENTS: • Supply web and life cycle • Growth, profit, optimal efficiency • Classic plus life cycle perspective • Business management and resource management • Classic plus LCA, WRI CO2 EMS, DFE, GRI, E-Goals, LEED

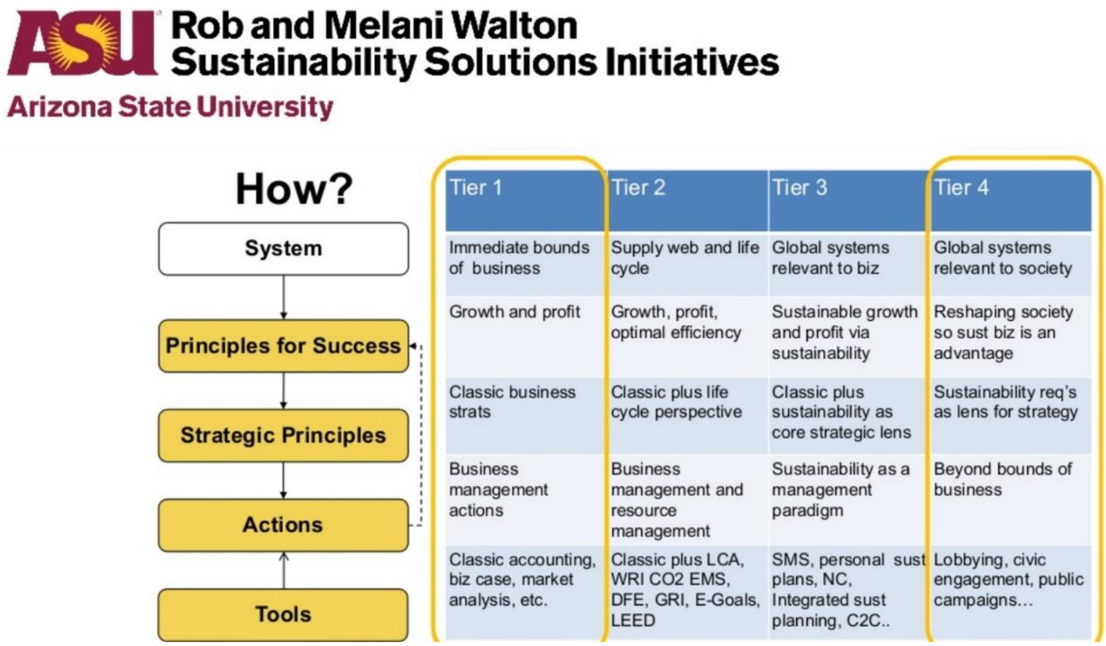
The **"Tier 2 and 3 requirements"** refers to the ranking of sustainability ambition for companies created by Dr. George Basile at Arizona State University. The LCA provides an environmental assessment of the products, but not the companies that produce them. Therefore, external sources on Nestlé's sustainability performance covered this dimension.

The Tier Requirements applied a systems-thinking strategic approach to understand and rank sustainability motivation for companies (*Transformative Organizational Success through Leadership*, 2017).

4 Tiers

- **Tier 1**- Compliance Focused
- **Tier 2**- Eco-efficiency beyond compliance
- **Tier 3**- Sustainability Integrated into the core strategy
- **Tier 4**- Organizing to change society

Each tier includes 5 requirements. As the tiers increase, so do the difficulty for companies to achieve the requirements. Therefore, the sustainability performance of a Tier 4 company greatly surpasses that of a Tier 1 company (See Figure below).



Tier 1	Tier 2	Tier 3	Tier 4
Immediate bounds of business	Supply web and life cycle	Global systems relevant to biz	Global systems relevant to society
Growth and profit	Growth, profit, optimal efficiency	Sustainable growth and profit via sustainability	Reshaping society so sust biz is an advantage
Classic business strats	Classic plus life cycle perspective	Classic plus sustainability as core strategic lens	Sustainability req's as lens for strategy
Business management actions	Business management and resource management	Sustainability as a management paradigm	Beyond bounds of business
Classic accounting, biz case, market analysis, etc.	Classic plus LCA, WRI CO2 EMS, DFE, GRI, E-Goals, LEED	SMS, personal sust plans, NC, Integrated sust planning, C2C..	Lobbying, civic engagement, public campaigns…

Figure 4: Tier Requirements. Source: Transformative Organizational Success through Leadership, 2017

Looking at Nestlé's sustainability progress and goals in their 2019 Annual Report, I would classify them as Tier 2- Eco-efficiency beyond compliance. For the KIF, I included all 5 of the requirements for this tier. Nestlé has been conducting LCAs in addition to their baby products, including one for its Nespresso product in 2009. Conducting LCAs to improve sustainable decision-making reveals that this company looks beyond environmental-compliance and cares about the life cycle impacts (*Life Cycle Analysis- Reducing our footprint*). Additionally, they reported progress in reducing plastic waste, making healthy food more affordable, promoting sustainable consumption, and mitigating climate change (*Annual Review*, 2019).

To accurately categorize Nestlé as a Tier 2 company, I also looked at their sustainability ranking and goals. In 2016, they made the list for the Global 100 Most Sustainable Corporations that evaluates companies on environmental, social, and economic performance (*Global 100 Most Sustainable Corporations*, 2016). However, they have not been ranked again on that list since then. Nestlé commits to reach zero net GHG emissions by 2050 and 100% of packaging recyclable or reusable by 2025 as part of Ellen MacArthur's New Plastics Economy initiative (*Nestlé to invest €1.68 billion in sustainable packaging*, 2020).

10. KIF Dimension: Value Chain Position

Value chain position	Use-phase

The **"Value chain position"** refers to the activity within the full range of steps needed to produce a product or service. The glass jar primarily functions for consumers to use, hence the "use-phase" to provide a baby food meal within the glass packaging.

11. KIF Dimension: Scale Requirements

Scale Requirements	Small or large companies can purchase bulk glass containers from a manufacturer. Scaling up operations can include building a glass manufacturing plant (~$150 million)

The **"Scale requirements"** refers to the ability for the innovation (glass jar) to be adopted by all or only by large organizations. The LCA implies that the glass jar was created at scale, due to its global presence in the baby food industry but lacks information on scalability. External sources on glass jar scalability covered this dimension. In short, small organizations buy glass jars in wholesale but might require partnering with larger organizations to scale up.

According to the European Container Glass Federation, glass packaging production increased by almost 40% in the last 25 years, contributing to 9 billion euros to the EU annual GDP. (*New Life Cycle Assessment Proves Industry Success*, 2017). This makes the glass packaging an established and scaled-up industry. The Ardagh Group, a global glass packaging producer, operates 100 facilities in 25 countries (*Ardagh Group Annual Report*, 2019). They lead the glass packaging industry in the US and include many food and beverage industry giants including Nestlé (*Acquisition of Anchor Glass*).

The LCA used the example of Nestlé's 200-g (7oz) glass jar. To get an estimate on the cost for a similar container, I looked at a jar sold by Ardagh that sells straight from the manufacturer to the client. They sell a 9oz jar for $737 per pallet (2,500 bottles) at many distribution sites throughout the US. A company that wishes to sell a similar product like Nestlé's baby food jar can operate at a small scale or on a large scale like some of Ardagh's clients: Heineken, Heinz, Nestlé, Procter and Gamble, Coca Cola (*Acquisition of Anchor Glass*).

A less popular, but effective scaling strategy could require a company to fund a new glass manufacturing plant. One example includes Gallo Glass, a subsidy of Gallo Winery. Located in Central Valley, CA, they amassed 60 years of glass manufacturing innovation to produce glass bottles for their wine and spirits (*About Us*). In 1958, Gallo Glass purchased its first glass furnace for bottle production. They purchased 4 more within 14 years that operate 24/7. In the 1980s, due to a heightened awareness of environmental concerns, Gallo Glass started to invest in technology for better efficiency and resource savings. Their innovative strides made them the largest glass plant in North America for wine and spirits (*Raise your Glasses, 2018).* Although Gallo did not disclose the capital costs to build their glass manufacturing plant, the acquisition costs of other plants give a close estimate.

To estimate the cost to purchase one glass manufacturing plant, I took the average of the major acquisition costs by Ardagh from 2012 to 2014 to purchase plants from Leone Industries Inc, Anchor Glass, and VNA. It averaged out to $150 million per glass manufacturing plant. Having a self-owned glass manufacturing plant will require other expenses, including "high levels of maintenance capital expenditures" (*Ardagh Group Annual Report*, 2019).

12. KIF Dimension: Value Chain Synergies

Value chain synergies	End-of-life recycling: Glass Recycling Technology: glass breaker (metal discs) to break the glass and minimize contaminants (i.e. fiber and plastics), magnets and eddy currents to separate metal, furnace to melt glass, and molds to form new containers.

The **"Value chain synergies"** refers to other value chain nodes that enable or are enabled by the innovation. After customers use the baby food within the glass jar, they dispose of it. Therefore, recycling follows the use-phase in the value chain. Although the LCA provides recycling rates, it does not provide information on the recycling technologies and processes for the products. Therefore, external sources on glass recycling technology covered this dimension.

According to another LCA by the Glass Packaging Institute, glass remains the only packaging material for food and beverages with endless recyclability without loss of the original quality or purity. Recycling glass has environmental and economic benefits due to lower demands for energy, lower CO2 emissions, and lower resource use extraction (*Environmental Overview*, 2010) Comparing recycling to landfill and waste-to-energy for packaging materials, another study concluded that recycling increases jobs and boosts the economy more than when the material fails to reenter the supply chain (Ferrão et al., 2014). Recycling glass requires its own "enabling technologies" described below:

Glass recycling started in the late 1960s. Mechanical processes crushed and screened the glass. During the 1980s, new technologies such as optical sorters allowed better removal of contaminants, sorting of glass colors, enabling more recycled content of glass (*Glass Recycling- Current Market Trends, 2018)*. The glass recycling process at a recycling plant in Jersey City, N.J., USA provides a great example of the recycling technology (Vo, 2013):

1. Machines crush glass and transport onto a conveyor to separate from other recyclables
2. Magnets remove small pieces of metal with a magnet. Eddy currents separate larger metals using a magnetic field.
3. Optical sorters use air jets to blow clear glass to separate from colored glass
4. The crushed, separated glass enters the trucks to send to the manufacturers

5. Machines mix the crushed glass and placed into a furnace to form a liquid at 2,700 °F
6. Molten glass cures and machines cut them into like-size portions
7. Liquid glass pours into a mold and cools into a finished product

Although transporting, treating, and melting glass produce emissions, recycling glass cutlets can offset them during manufacturing. According to a 2010 LCA by the Glass Packaging Institute, "the increase of recovery and recycling results in a decrease of the primary energy demand (PED) and an even greater decrease of global warming potential (GWP)" (*Environmental Overview Complete Life Cycle Assessment*, 2010). 35 states host about 80 recycled glass processors in the US (*Benefits of Glass Packaging*). Therefore, glass recycling as a value chain synergy contributes to the circularity of glass packaging.

The glass recycling market as of 2019 increased its annual growth from $1,900 million in 2014 to $2,460 million in 2018. It is projected that the market size will continue to grow to $3,440 million by 2023 (*Global Glass Recycling Market Report*, 2019). This supports the push for more glass recycling in the value chain.

KIF Analysis 2: Plastic Pot (Linear Product)

Like the KIF Analysis 1 for the glass jar, I filled out the KIF template for the plastic pot to address the 12 dimensions:

Table 4

The KIF Template (Analysis 2: Plastic Pot)

Dimension	Description
Innovation category name	Nestlé Plastic (PP) Baby Food Pot 200-g
Description	The innovation includes a plastic pot, lidding film, cap, label. Functional unit: provide a proper vehicle for a child's baby food meal in France, Spain, and Germany in 2007
State of development	Developed and commercialized
Effect on circularity	Plastic pots have a reuse rate of 35% as a substituting fuel/reducing agent to avoid burdens in the cement/fuel industry in light fuel oil, a recycling rate of 40% to avoid virgin production, and an incineration rate of 25% for electricity and heat generation to avoid electricity from the grid
GHG impact	Compared to the glass jar, the plastic pot has decreased impacts: 13% less for primary energy, 3% less for global warming, 3% less for terrestrial acidification/nutrification
Other environmental impacts	Carcinogens, Terrestrial Ecotoxicity, Aquatic Ecotoxicity, Photochemical Oxidation, Non-carcinogens, Respiratory Inorganics, Ionizing Radiation, Ozone Layer Depletion, Land Occupation, Aquatic Acidification, Aquatic Eutrophication, Mineral Extraction
Social impacts	Health and safety, socio-economic repercussion, human rights, development of country
Enabling technologies	Plastic Pot Manufacturing: Injection of melted plastic, cooling, and ejecting
Tier 2 and 3 requirements	TIER 2 REQUIREMENTS: • Supply web and life cycle • Growth, profit, optimal efficiency • Classic plus life cycle perspective • Business management and resource management • Classic plus LCA, WRI CO2 EMS, DFE, GRI, E-Goals, LEED
Value chain position	Use-Phase
Scale requirements	Small or large companies can purchase bulk plastic containers from a manufacturer. Scaling up operations can include building a plastic manufacturing plant (~$2.5 million)
Value chain synergies	Waste to energy treatment plants, plastic shredders for substitution fuel, and recycling technology

1. KIF Dimension: Innovation Category Name

Innovation category name	Nestlé Plastic (PP) Baby Food Pot 200-g

The **"Innovation category name"** dimension refers to the material for the analysis: a 200-g plastic (PP) baby food pot provided by Nestlé.

2. KIF Dimension: Description

Description	The innovation includes a plastic pot, lidding film, cap, label. Functional unit: provide a proper vehicle for a child's baby food meal in France, Spain, and Germany in 2007

The **"Description"** dimension refers to components of the "innovation": the plastic pot as described by its functional unit in the LCA.

3. KIF Dimension: State of Development

State of development	Developed and commercialized

The **"State of development"** dimension refers to the product development stage (i.e. lab-only, early development). The LCA, like for the glass jar, provided some information on this but required supplemental external sources to provide more detail. Nonetheless, the sources revealed that the plastic pots fall under "Developed and Commercialized".

Based on the product label shown on the figure in Humbert et al.'s LCA (See figure below), the plastic pot referred to Nestlé's German baby food band, NaturNes. Today, Nestlé still advertise NaturNes and sell them globally, specifically in Europe *(NaturNes).* Therefore, I assume that the plastic pots fall under this state of development.

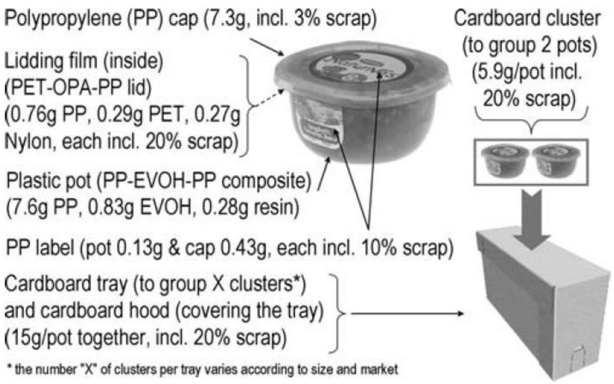


Figure 5: Plastic Pot Components. Source: (Humbert et al. 2009)

4. KIF Dimension: Effect on Circularity

Effect on circularity	Plastic pots have a reuse rate of 35% as a substituting fuel/reducing agent to avoid burdens in the cement/fuel industry in light fuel oil, a recycling rate of 40% to avoid virgin production, and an incineration rate of 25% for electricity and heat generation to avoid electricity from the grid

The **"Effect on circularity"** dimension refers to how the innovation impacts circularity through its value chain. Like the glass jar, the LCA also lacked information on how the plastic is reused into other technical cycles. Additionally, some of the waste management data were unsupported by clear sources. External sources on plastic waste management data covered this dimension.

According to Humbert et al.'s LCA on end-of-life analysis, plastic pots have a reuse rate of 35% as a fuel substitute for the cement/fuel industry, a recycling rate of 40%, and an incineration rate of 25% (2009). Different data sources for each of the end-of-life percentages make the reliability of this data unclear. The reuse rate was not attributed to any of the three countries. In contrast, the recycling and incineration rates came from Germany's data. Like the waste management data on the glass jars, the data on plastic waste diversion lacks transparency and credibility to provide evidence for the end-of-life pathway for the plastic pot in the figure below.

Germany has a recycling rate of about 16% for plastics. Despite the amount of plastic exported, it does not reflect the amount of closed-loop recycling for a circular economy (Dean, 2019). Therefore, the study's 40% recycling might represent the number of recyclables processed in other countries, instead of within Germany to close the loop.

5. KIF Dimension: GHG Impacts

GHG impact	Compared to the glass jar, the plastic pot has decreased impacts: 13% less for primary energy, 3% less for global warming, 3% less for terrestrial acidification/nutrification

The **"GHG impacts"** dimension refers to the greenhouse gas environmental impacts. The KIF analysis for the glass packaging above shares the same 3 LCA indicators: primary energy, global warming, and terrestrial acidification/nutrification.

6. KIF Dimension: Other Environmental Impacts

Other environmental impacts	Carcinogens, Terrestrial Ecotoxicity, Aquatic Ecotoxicity, Photochemical Oxidation, Non-carcinogens, Respiratory Inorganics, Ionizing Radiation, Ozone Layer Depletion, Land Occupation, Aquatic Acidification, Aquatic Eutrophication, Mineral Extraction

The **"Other environmental impacts"** dimension refers to impacts other than greenhouse gas impacts that affect the environment. The KIF analysis for the glass packaging above shares the same 12 LCA indicators (i.e. carcinogens and terrestrial ecotoxicity).

7. KIF Dimension: Social Impacts

Social impacts	Health and safety, socio-economic repercussion, human rights, development of country

The **“Social impacts”** dimension refers to impacts on the lives of people involved (Umair et al., 2015). Like the glass jar, external sources on social impact categories on the informal recycling sector for plastics covered this dimension.

According to a literature survey, informal recyclers in developed countries such as Germany suffer from social impacts like those in developing countries. Informal recyclers in developed countries recycle to earn a comparable standard of income with the formal sector, whereas those in developing countries recycle to make enough money to survive (Gërxhani, 2004). The social impacts in Germany’s informal recycling sector appear like those experienced in France, identified by a 2015 Social LCA as health & safety, socio-economic repercussion, human rights, and development of country (Umair et al., 2015).

8. KIF Dimension: Enabling Technologies

Enabling technologies	Plastic Pot Manufacturing: Injection of melted plastic, cooling, and ejecting

The **"Enabling technologies"** refers to the technology that drives the cost and performance of the innovation. For a plastic pot, that technology describes the plastic manufacturing process. Like the glass jar, external sources on plastic manufacturing covered this dimension.

According to an LCA on plastic packaging in the US, manufacturers use injection molding to form plastic disposable food containers:

- Machines heat up plastic resin (derived from fossil fuels) and inject them into a mold in an inverse shape to the final product.

- The cool walls of the mold solidify the melted plastic
- When the plastic finishes cooling, the mold opens to eject the finished product

9. KIF Dimension: Tier 2 and 3 Requirements

Tier 2 and 3 requirements	TIER 2 REQUIREMENTS: • Supply web and life cycle • Growth, profit, optimal efficiency • Classic plus life cycle perspective • Business management and resource management • Classic plus LCA, WRI CO2 EMS, DFE, GRI, E-Goals, LEED

The **"Tier 2 and 3 requirements"** refers to the ranking of sustainability ambition for companies created by created by Dr. George Basile at Arizona State University. Since the glass jar and plastic pot are both made by the same brand, Nestlé, they both require external sources to cover this dimension. The tier requirements are identical for products from the same company.

10. KIF Dimension: Value Chain Position

Value chain position	Use-phase

The **"value chain position"** refers to the activity within the full range of steps needed to produce a product or service. Like the glass jar, the plastic pot primarily functions for consumer use, hence the "use-phase" to provide a baby food meal within the glass packaging.

11. KIF Dimension: Scale Requirements

Scale Requirements	Small or large companies can purchase bulk plastic containers from a manufacturer. Scaling up operations can include building a plastic manufacturing plant (~$2.5 million)

The **“Scale requirements”** refers to the ability for the innovation (plastic pot) to be adopted by all or only by large organizations. Like the glass jar, the plastic pots require external sources to cover this dimension, specifically on plastic production scalability. Like the glass jars, small organizations buy plastic pots in wholesale but might require partnering with larger organizations to scale up.

Polypropylene resin production grows every year, with the 3rd and 4th countries with the largest production being Europe and North America, respectively as of 2016 (*All About Polypropylene*). According to a recent article amidst the current COVID-19 pandemic, experts expect the global plastic packaging market to grow from its current $244 billion market size to $320 billion by 2027 (Kimani, 2020). This makes the plastic industry an established and scaled-up industry.

The LCA used the example of Nestlé’s 200-g (7 oz) plastic pot. If a company wants to sell food-safe plastic PP containers, they can partner with a plastic designer/manufacturer like Placon, the leader in North America for packaging design. Using 3D design, prototype testing, and production, plastic manufacturers can help scale up a product for commercialization to get the product to market. Their injection molding products include tamper-resistant, BPA free, and recyclable 7oz PP jars. (*Custom Food Packaging Solutions*).

One way of scaling up production involves building a plastic manufacturing plant. In a 2017 report, consultants estimated the operating costs for 8 plastic manufacturing plants in the Northeastern US. For a 175,000 sq. ft. facility that can employ 225 workers, the construction in a metro region costs about $2.5 million for 25+ acres. (*Comparative Plastics Industry Manufacturing Operating Costs*, 2017).

12. KIF Dimension: Value Chain Synergies

Value chain synergies	Waste to energy treatment plants, plastic shredders for substitution fuel, and recycling technology

The **"Value chain synergies"** refers to other value chain nodes that enable or are enabled by the innovation. According to the LCA study, the plastic pots have a reuse rate of 35% as a fuel substitute for the cement/fuel industry, a recycling rate of 40%, and an incineration rate of 25% (Humbert et al., 2009). Like the glass jar, recycling follows the use-phase in the value chain. Additionally, external sources on plastic recycling technology covered this dimension.

The cement industry represents one of the largest in the world, with fossil fuels being their main resource for cement production. The need for lowering operating costs and reducing environmental impacts increases the demand for alternative fuels. A 2018 LCA study illustrated the impacts of using non-recycled plastics (i.e. plastic #3 PVC) as a fuel substitute for cement plants in the US. The researchers concluded that engineered fuel using waste plastics and paper can reduce energy and greenhouse gas emissions without adverse effects on the quality of cement or cause other environmental impacts. (Bourtsalas et al., 2018). Therefore, having 35% of plastic pots used for waste-to-energy can still help reduce emissions due to substitution although it does not promote a circular economy by keeping materials in the supply chain.

Polypropylene (PP), a plastic commonly found as household items like shampoo bottles or yogurt containers, has difficulty being recycled. According to a 2018 report by the American Chemistry Council, PP plastic has about a 17% recycling rate in the U.S. (*United States National Postconsumer Plastic Bottle Recycling Report*, 2018).

It is difficult and expensive to purify the resin from grey/black scented resin into clear, odorless resin. This makes it tough to recycle PP in packaging due to consumer's perception of safety and cleanliness with products. According to an article in 2019, Procter & Gamble Co. researchers invented a new patented technology to purify the recycled PP resin using 1/7 of the energy to make virgin PP resin. This required a $300 million-dollar plant to commercialize the scale of the operations, processing 119 million pounds of plastic waste a year and turning low-quality recycled resin into “virgin-like” resin (Chasan, 2019).

CHAPTER 3

RESULTS AND DISCUSSION

Summary of the KIF Analysis on the Nestlé Plastic (PP) Pot vs Glass Jar

I conducted two separate KIF analyses for the Nestlé plastic pot and glass jar. Below I filled out a third KIF template to analyze the results from both products, highlighting CE dimensions in green that could be answered with the LCA and orange for the dimensions that the LCA did not address well. Of the 12 CE dimensions, the LCA covered 6 of them.

Table 5

The KIF Template (Summary of the Dimensions Addressed by the LCA)

Dimension	Description
Innovation category name	The LCA easily identified the innovations (Nestlé plastic pot and glass jar).
Description	The LCA described the functional unit (provide a proper vehicle for a child's baby food meal)
State of development	The LCA did not include information on the state of development of the product in scope
Effect on circularity	The LCA provided percentages on different end-of-life scenarios (i.e. landfill, incineration, recycling). However, the LCA lacked data on the recycling process, end-markets, secondary material streams, etc. External sources answered this dimension.
GHG impact	The LCA identified indicators on GHG impacts for the innovations (i.e. Primary Energy, Global Warming, Terrestrial Acidification).
Other environmental impacts	The LCA identified environmental indicators other than GHG impacts (i.e. Terrestrial Ecotoxicity, Aquatic Ecotoxicity).
Social impacts	A few LCA indicators fall into the category of "human health", or "social impact": Carcinogens, Non-carcinogens, Ionizing Radiation. However, they lacked social impacts on

	other stakeholders (i.e. human rights of workers). External sources answered this dimension.
Enabling technologies	The LCA focused on the impacts of the technologies rather than the technologies themselves. Therefore, external sources answered this dimension on the technologies to produce plastic and glass.
Tier 2 and 3 requirements	The LCA lacked information on Nestlé. External sources answered this dimension regarding Nestlé's sustainability ranking and their relationship to the tiers
Value chain position	The LCA identified the value chain position based on the goal and scope of each innovation.
Scale requirements	The LCA did not include scalability, so external sources answered this dimension regarding the financial capital and technologies required to scale up plastic and glass packaging production.
Value chain synergies	After using food packaging, end-of-life management follows next in the value chain. However, the LCA does not describe the recycling processes, so external sources answered this dimension.

When conducting the KIF analyses, I often had to search for external sources to answer questions such what technology produces the plastic packaging, or how recycling equipment process glass cutlets in the cement industry. Although LCA tools provide information on the environmental impacts of products, they lack CE analysis on reuse/multiple life cycles of products. External sources such as industry reports, scientific papers, and news articles helped to answer some gaps in the KIF analysis that were not covered by the LCA. Other CE-based and LCA-based tools might help supplement KIF's assessment data to address the 7 CE dimensions that a stand-alone LCA cannot:

- State of Development
- Effect on Circularity
- Social Impacts
- Enabling Technologies

- Tier 2 and 3 Requirements
- Scale Requirements
- Value Chain Synergies

Comparing and Contrasting CE-Based and LCA-Based Tools

This strategy follows a similar study where researchers compared an LCA with the European Environment Agency's five CE requirements (reducing inputs, increasing renewables, reducing emissions, reducing material losses, increasing product durability). They concluded that the LCA met 3 of them (reducing inputs, reducing emission levels, reducing material losses), and identified other CE indexes that address circularity beyond the LCA (i.e. Material Circularity Indicator (MCI), Material Flow Accounting (MFA)) (Lonca et al., 2018). Similarly, I will compare the LCA with the 4 analytical tools to identify which tools can theoretically meet the 7 remaining KIF dimensions. Below are descriptions of each tool and what KIF dimensions they address.

1. World Business Council for Sustainable Development (WBCSD)- Circular Transition Indicators (CTI)

In 2019, the WBCSD created a CE-based tool called the CTI, a CE self-assessment framework to measure circularity for company decision-making. It offers companies insights into their CE Performance and complements existing frameworks. However, it is not a sustainability assessment itself; only a compliment. Although it does help to understand circular material flow and business performance, it does not help understand the environmental and social impacts of the company's activities or compare companies/products.

Examples:

Chemical Company, Royal DSM, aims to preserve natural resources and utilize limited resources available. They used the CTI to set a baseline and monitor their progress towards CE. The CTI helped them to begin regularly collecting "circularity data" on material flows so different groups in the business can have engaging conversations the CTI results. They also mention that by identifying circularity gaps, it can help them innovate new circular inventions or business models. (*Circular Transition Indicators Case Studies*, 2020).

Appliance manufacturer, Whirlpool, aims to use CTI to enable them to reach their goals, such as reducing the use of plastics. Whirlpool gained insights from looking at their Bill of Material (BOM) to understand which materials for their products (i.e. washing machines) are being recycled in open vs closed loops. It's inspiring innovations in how they can increase their recycled content in their machines. (*Circular Transition Indicators V1.0*, 2020).

CTI Framework:

- **Inflow:** How circular are the materials the company sources?
- **Outflow- recovery potential:** How does the company design and processes its material to be technically recovered?
- **Outflow- actual recovery:** How much of the company's outflow is recovered?

Data Requirements:

The CTI online tool allows value chain discussions between the users and internal stakeholders. Data is obtained through the tool without raising privacy or confidentiality concerns. Below are the data requirements:

- Close the loop:
  - % circular inflow
  - % circular outflow
  - % water circularity
  - % renewable energy
- Optimize the loop:
  - % critical material
  - % recovery type
- Value the loop:
  - Circular material productivity

Using information from the *Circular Transition Indicators V1.0*, 2020 user guidebook, I filled out the Taxonomy C-Indicator categories below to synthesize and classify the CTI:

Table 6

Classification of the CTI using the Taxonomy C-Indicator Categories

Taxonomy C-Indicator Categories	Circular Transition Indicators (CTI)
Implementation Level	Micro-level (products)
Circularity Loop(s)	Reuse, Remanufacture, and Recycle (considers all circularity loops except "Maintain")
Performance	Intrinsic (focuses on material flows and performance rather than environmental or social impacts)

Perspective of Circularity	Actual Circularity (uses previous company recovery data)
Usages	Information Purposes, Decision-Making Purposes, Communication (not required), and Learning
Transversality	General
Dimension	Single
Units	Quantitative (%)
Format	Web-based tool: CTI Tool
Sources	Industrial Companies

Comparing and Contrasting LCA to KIF and CTI:

LCA, like CTI, does well to measure the inflows and outflows of material. However, LCA solely focuses on the product's environmental performance and not that of the company. Therefore, LCA does not examine at how a company sources, processes, or recovers the material. It has a narrow scope and does not always view the product as part of a system. The KIF generally looks at the same dimensions as the CTI (i.e. Close the loop) but lacks specific circularity metrics (i.e. % critical material). However, the KIF looks at more dimensions of CE to include environmental and social impacts rather than just material flows.

KIF dimensions that the CTI addresses that the LCA does not:

- Effect on Circularity
- Enabling Technologies
- Value Chain Synergies

2. Ellen MacArthur Foundation (EMF)- Material Circularity Indicator (MCI)

In 2015, the EMF created a CE-based tool called the Material Circularity Indicator (MCI) tool for companies to identify and measure the circular value at the product-level or company-level to improve CE design and procurement. It considers many material loops and ultimately provides users a value between 0 and 1, 1 being higher in circularity (*Circularity Indicators*, 2015).

Examples:

The Widget Store used the MCI to compare the circularity of their different mechanical products. They select a product for their scope, get the BOM from the product managers, and then analyze the recycling/reuse loops. When comparing two products, such as a standard widget made of 80% ABS plastic and 20% aluminum verses a premium widget made of 80% aluminum and 20% ABS plastic, the MCI generated a score for easy comparison. For the MCI score from 0 to 1, 0 is less circular whereas 1 is most circular. The standard widget scored 0.06 whereas the premium one scored 0.61. This led to the design for a more circular widget, that incorporates 86% aluminum and 14% plastic, uses less material, and uses recycled feedstocks. The Widget Store also started to introduce a new closed loop return system to get the widgets back from customers after use *(Non-Technical Case Studies, 2015).*

The ACME Company has a product line of electronic tablets. The tablet designer looked at the material composition of the tablets and found that it uses 100% virgin materials and had a product span of 2 years. Using the MCI, the designer noticed that the main carbon emissions are due to the electrical components and that the rare earth metals contributed most to the high price. The designer focused on improving the case and front glass cover of the tablet by designing the front glass cover to be easily reused and switching the plastic casing with aluminum. The original tablet scored 0.10 on the MCI, whereas the newer tablet with less plastic and more reusable components, scored 0.46. This led to less landfill waste and higher reuse of materials. The ACME company are actively looking for other innovative ways to reduce their carbon footprint while keeping costs low. *(Non-Technical Case Studies, 2015).*

The 4 MCI Inputs:

- **Production:** How much input is coming from virgin, recycled, and reused materials?
- **Use:** How long is the product used in comparison to a similar one?
- **Destination after use:** How much material goes to reuse, recycling, or landfill?
- **Efficiency of recycling:** How efficient is the recycling processes used for recycled materials?

Data Requirements:

- Bill of Materials: the amount of virgin, reused, and recycled materials and components
- Lifespan of product relative to its industry (including repair and maintenance)
- End-of-life pathways of the products and its parts after use
- Efficiency of the recycling process for the product

Using information from the *Circularity Indicators*, 2015 user guidebook, I filled out the Taxonomy C-Indicator categories below to synthesize and classify the MCI:

Table 7

Classification of the MCI using the Taxonomy C-Indicator Categories

Taxonomy C-Indicator Categories	Material Circularity Indicator (MCI)
Implementation Level	Micro-level *(products and companies)*
Circularity Loop(s)	Maintain, Reuse, Remanufacture, and Recycle
Performance	Intrinsic *(focuses on material flows and performance rather than environmental or social impacts)*
Perspective of Circularity	Actual Circularity *(uses previous company recovery data)*
Usages	Communication *(materials/products comparison)* and Learning *(to know what and how natural resources we depend on)*
Transversality	General
Dimension	Single
Units	Quantitative (%)
Format	Excel Spreadsheet
Sources	Industrial Companies

Comparing and contrasting LCA to KIF, CTI, and MCI:

Comparing the taxonomy analysis to that of the CTI in the previous section, MCI is very similar. In short, MCI focuses more on circularity loops and how stakeholders can learn from the CE assessment, whereas CTI focuses more on information gathering and decision-making for products designed for reuse/recycling (not necessarily for durability). The differences are shown in the following taxonomy categories:

- *Circularity Loops*- MCI includes *Maintain* (design for durability), but CTI does not
- *Usages*- CTI includes *Information-Purposes* and *Decision-Making Purposes, but MCI does not*
- *Format*- CTI uses a web-based tool, whereas MCI uses an excel spreadsheet. Both are free for users.

LCA includes material inputs and outputs, like both the CTI and MCI frameworks. However, MCI focuses more on the material properties and loops (i.e. efficiency of recycling) in comparison to CTI that also looks at resources (i.e. % renewable energy input). MCI results in an overall score for circularity from 0 to 1, whereas CTI gives percentages for different indicators that the user can choose to include. Both, however, lack the environmental impacts (i.e. GHG emissions) and social impacts (i.e. human rights) that the KIF includes in its framework.

In literature, researchers commonly conduct an MCI analysis in conjunction with LCA. In a study by Gue et. al., they looked at the environmental sustainability of two different biodiesels using both MCI and LCA. They used LCA to address environmental impacts and MCI to provide a quantitative circularity value for comparing the two products. The LCA identified which processes and sources to change for lower emissions, whereas the MCI identified which nutrients to recycle to avoid the use of virgin materials (Gue et al., 2018). Each tool served different purposes and contributed towards the CE analysis between the two products.

KIF Dimensions that the MCI addresses that the LCA does not:

- Effect on Circularity
- Tier 2 and 3 Requirements
- Value Chain Synergies

3. US Environmental Protection Agency (EPA)- Sustainable Materials Management (SMM) Prioritization Tools

In 2019, The EPA released the LCA-based tool called the Sustainable Materials Management (SMM) Prioritization Tools. Users an input a good/service into the online tool, which will generate an environmental profile, supply chain/operations, impactful purchases, and supply chain hotspots. The tool quickly generates over 20 indicators for impact that are categories based on: Environmental significance, supply chain/ operations, purchases, supply chain hotspots. These lifecycle-based tools have about 20 environmental, human health, and socio-economic indicators on goods and services at the national, state, and organizational levels. It gives users an accessible way to measure a product's production, use, and disposal. (*User Manual for the Sustainable Materials Management Prioritization Tools*, 2020)

Example:

I used the SMM Prioritization Tools on both types of packaging in the comparative LCA that I analyzed: Plastics and Glass. As an LCA-based tool, the SMM only produced results on environmental impacts and identified environmental hotspots.

- SMM Results for Plastic Packaging:
    - The three potentially significant environmental issues:
        - Commercial RCRA Hazardous Waste
        - Ozone Depletion
        - Energy Use
    - Supply Chain Hotspots:
        - Other basic inorganic chemicals
        - Plastic
        - Unrefined oil and gas
    - More impacts due to the supply chain than operations
- SMM Results for Glass Packaging:
    - The three potentially significant environmental issues:
        - Smog Formation
        - Commercial RCRA Hazardous Waste
        - Energy Use
    - Supply Chain Hotspots:
        - Glass and glass products
        - Other basic inorganic chemicals
        - Unrefined oil and gas
    - More impacts due to supply chain than operations

The SMM Prioritization Tool provided information about the retrospective impacts of linear products, but lacked circularity categories that would spark innovation and creativity into the design of new products.

The 5 SMM indicator categories:

- **Impact Potential** (i.e. GHGs, Human Health-Respiratory Effects)
- **Resource Use** (i.e. Energy Use, Water Use)
- **Chemical Releases** (i.e. Hazardous Air Pollutants, Pesticides)
- **Waste Generated** (i.e. Commercial Construction & Demolition Debris)
- **Economic & Social** (i.e. Jobs Supported)

Data Requirements:

The user does not need to input data from their own dataset on goods/services to analyze. The only data they need to input is the name of the good/service to analyze. The SMM Prioritization tool uses EPA's United States Environmentally-Extended Input-Output (USEEIO) model that calculates impacts based on publicly available data for national averages on a wide variety of goods/services most relevant to the user's input. Using information from the *User Manual for the Sustainable Materials Management Prioritization Tools*, 2020, I filled out the Taxonomy C-Indicator categories below to synthesize and classify the SMM Prioritization Tools:

Table 8

Classification of the SMM using the Taxonomy C-Indicator Categories

Taxonomy C-Indicator Categories	Sustainable Materials Management (SMM) Prioritization Tools
Implementation Level	Micro-level *(products) and* Macro-level *(city, province, region, or country)*
Circularity Loop(s)	N/A
Performance	Consequential *(focuses on environmental impacts, resource use, chemical releases, waste generated, and economic/social impacts)*
Perspective of Circularity	Actual Circularity *(uses previous input-output data)*
Usages	Information Purposes *(Understanding the overview of environmental issues and resource use)* and Learning *(Educating professionals how to use the tool to find improvement opportunities*)
Transversality	General
Dimension	Single
Units	Quantitative (%)
Format	Web-based tool: SMM Prioritization Tool
Sources	Industrial Companies

Comparing and contrasting LCA to KIF, CTI, MCI, and SMM Prioritization Tools:

Like LCA, CTI, and MCI, the SMM Prioritization Tool does well to measure the flows of material over their life cycle to identify areas for environmental improvement. However, unlike CTI and MCI, the tool does not provide indicators to measure end-of-life management such as CTI's Circular Material Productivity metric or MCI's Efficiency of Recycling metric. Furthermore, the SMM Prioritization Tool requires very little user-inputted data, so the results are based on national data embedded within the online tool. Additionally, the tool includes environmental impact indicators like those commonly found in LCA's, but like LCA's they lack many social indicators. Although the SMM Prioritization tool includes indicators on job creation and value-added to the economy, it lacks crucial social factors such as human rights. The KIF may not have specific environmental, human health, and socioeconomic indicators like the SMM Prioritization tool, but it covers a broader scope of the circular economy by looking at dimensions such as Effect on Circularity and Social Impacts.

KIF Dimensions that the SMM Prioritization Tool addresses that the LCA does not:

- Social Impacts (job creation and value-added to the economy)

4. Social Life Cycle Assessments (SLCA)

In 2009, the UNEP (United Nations Environment Programme) and SETAC (Society of Environmental Toxicology and Chemistry) created an LCA-based tool called the Social Life Cycle Assessment. This framework follows the guidelines in the ISO 14040 and 14044 standards for a traditional LCA. In their map, the *Guidelines for Social Life Cycle Assessment of Products,* they present a framework for providing decision support on reducing social and socio-economic impacts within a product/service supply chain by identifying root causes, improvement opportunities, and where to implement collaboration (UNEP-SETAC et al. 2009):

Examples:

In 2012, a Social LCA was conducted on the informal recycling of electronic Information and Communication Technology (ICT) in Pakistan. Since most e-waste is produced in developed countries, but recycled in developing countries, social impacts in e-waste recycling facilities (i.e. in Pakistan) are important to measure. The purpose of the SLCA was to identify the full life-cycle social impacts to improve decision making on future ICT production. Site-specific and primary inventory data were collected for different stakeholders, including workers, the local community the society in Pakistan, and the value chain actors. The crude dismantling process to extract raw materials (i.e. plastics, aluminum, gold, silver, copper) were identified and inventory categories (i.e. working hours, health, economic development) were identified. This SLCA produced new data on social impacts of informal e-waste recycling that strives to spur new regulations, economic incentives, and business models to reduce negative health and social impacts while promoting employment in the community (Umair et al., 2015).

In 2013, a SLCA was conducted to identify social hotspots on steel and concrete building materials. The purpose was to assess the social impacts of the building materials along their entire life cycles to provide recommendations for affected stakeholders. Data was collected through material flow analysis and stakeholder interviews. The case study concluded that the steel had less negative social impacts than concrete, mainly due to impact categories such as socio-economic repercussions, health/safety, and working conditions. This has led to recommendations such as improving the eco-efficiency production of concrete using green technologies that uses alternative fuels, or improving the working conditions of coal miners and how the company conducts health/safety for its workers (Hosseinijou et al., 2014).

The 5 SLCA stakeholder categories and associated impacts:

- **Workers** (i.e. human rights)
- **Local Community** (i.e. working conditions)
- **Society** (i.e. contribution to economic development)
- **Consumers** (i.e. end of life responsibility)
- **Value Chain Actors** (i.e. fair competition)

Data Requirements:

- Desktop screening (via literature review and web search)
- Social audit (on-site data collection via social audits to analyze the relationships between the organization and stakeholders)
- Data on background information of the company and geographic area

Using information from the *Guidelines for Social Life Cycle Assessment of Products*, 2009, I filled out the Taxonomy C-Indicator categories below to synthesize and classify the SLCA:

Table 9

Classification of the SLCA using the Taxonomy C-Indicator Categories

Taxonomy C-Indicator Categories	Social Life Cycle Assessments (SLCA)
Implementation Level	Micro-level *(products)*, Meso-level (*symbiosis association, industrial parks)*, and Macro-level *(city, province, region, or country)*
Circularity Loop(s)	Maintain, Reuse, Recycle
Performance	Consequential *(focuses on social impacts as a result)*
Perspective of Circularity	Actual Circularity *(uses primary data)*
Usages	Information Purposes (understanding social impact concerns), Decision-Making Purposes (deciding between two products), Communication (to decision makers and stakeholders), and Learning (identifying social hotspots)
Transversality	General
Dimension	Single
Units	Quantitative (%) or Qualitative (attributes or characteristics of processes)
Format	Formulas
Sources	Academics, Industrial Companies, and Consulting Agencies

Comparing and contrasting LCA to KIF, CTI, MCI, SMM, and SLCA:

LCA does include some social impact indicators (i.e. human toxicity), but that may only target one of many social impact categories listed in the SLCA. LCA does not measure socio-economic impacts such as human rights or working conditions. In terms of CE assessment tools (i.e. CTI, MCI, SMM Prioritization Tools), only the SMM Prioritization tools include social impact metrics (i.e. jobs supported), which, like the LCA, only covers maybe one of the five SLCA stakeholder categories above. The CE assessment tools focus on the technical cycles and flow for materials and their environmental impacts instead of socio-economic conditions due to those materials. The KIF includes a CE dimension for social impact but does not have specific categories for measurement like the SLCA. Therefore, the KIF would benefit by including some categories and indicators from the SLCA for a more comprehensive social impact analysis that covers multiple stakeholders.

<u>KIF Dimensions that the SLCA addresses that the LCA does not:</u>

- Social Impacts

Addressing KIF Dimensions with CE-Based and LCA-Based Tools

Of the 4 analytical tools listed in the table below, WBCSD's CTI tool (created in 2019) and EMF's MCI tool (created in 2015) address the most KIF dimensions that an LCA cannot.

Table 10

Addressing the KIF with CE-Based and LCA-Based Tools

KIF Dimension	CTI	MCI	SMM	SLCA	LCA
1. Innovation Category Name	✔	✔	✔	✔	✔
2. Description	✔	✔	✔	✔	✔
3. State of Development					
4. Effect on Circularity	✔	✔			
5. GHG Impact			✔		✔

6. Other Environmental Impacts			✓		✓
7. Social Impacts			✓	✓	
8. Enabling Technologies	✓				
9. Tier 2 and 3 Requirements		✓			
10. Value Chain Position					✓
11. Scale Requirements					
12. Value Chain Synergies	✓	✓			

<u>Effect on Circularity:</u>

Both CTI and MCI address the *Effect on Circularity* dimension well since they look at material flows, specifically end-of-life reuse/recycling. CTI addresses the categories: Close the Loop, Optimize the Loop, and Value the Loop. MCI addresses the categories: Production, Use, Destination after Use, and Efficiency of Recycling. Either tool would suffice for the *Effect on Circularity* dimension. SMM almost addressed this dimension, except they only include indicators for commercial C&D, MSW, and hazardous waste and do not include indicators for reuse/recycling streams.

<u>Social Impact:</u>

Both SMM and SLCA addressed the *Social Impacts* dimension. The SLCA covered multiple stakeholders in a product's lifecycle (workers, local community, society, consumers, value chain actors). In terms of the SLCA stakeholder categories, the SMM covered workers and the local community only. Therefore, SLCA would be a better tool for the *Social Impacts* dimension.

Enabling Technologies:

CTI addresses the *Enabling Technologies* dimension by asking the user questions such as how their company designs and processes their material for recovery.

Tier 2 and 3 Requirements:

MCI addresses the *Tier 2 and 3 Requirements* dimension since their tool can apply to both the product and the company. The company circularity indicators can help categorize then in the different tiers based on their sustainability values and performance.

Value Chain Synergies:

The end-of-life phase follows next after the use-phase for the plastic and glass packaging materials. Therefore, CTI and MCI address this dimension since they include indicators for reuse/recycling for the *Effect on Circularity* dimension.

Summary of which CE-based and LCA-based tools best address the KIF dimensions:

The KIF required multiple analytical tools to address all its dimensions except *State of Development and Scale Requirements*, that both require external sources.

- *Effect on Circularity*- CTI or MCI
- *Social Impacts*- SLCA
- *Enabling Technologies*- CTI
- *Tier 2 and 3 Requirements*- MCI
- *Value Chain Synergies*- CTI or MCI

The findings of this thesis resemble the results of another study comparing LCA with MCI for the end-of-life of tires. In a study by Lonca et al., the authors concluded that LCAs typically quantify negative impacts for companies to reduce them, whereas MCI quantifies positive impacts for companies to increase them (2018). The forward-thinking approach of CE-based tools verses the backward-thinking approach of LCA-based tools illustrates the need for both to drive economic activity while reducing undesirable environmental and socio-economic effects. Likewise, the LCA from this analysis requires CTI, MCI, and SLCA plus external sources to successfully address all of the KIF dimensions for a wholistic CE assessment.

CHAPTER 4

CONCLUSION

The case study of the KIF on the comparative LCA on plastic and glass packaging highlighted both the pros and cons of using LCA data for a wholistic CE assessment. LCA proved useful in providing environmental impacts of each product at each stage of their life cycle. It fell short, however, when looking beyond LCA indicators to address other dimensions of CE, specifically resource use efficiency (i.e. effect on circularity, social impact, value chain synergies). LCA lacked information on the processes to produce the materials, the human labor to recycle the materials, and the technology required to reprocess the material into other technical cycles. This is mainly because LCA was designed to answer questions for products made for the linear, rather than the circular economy. Data from the LCA covered 5 out of 12 KIF dimensions: *Innovation Category Name, Description, GHG Impact, Other Environmental Impacts, and Value Chain Position.*

I analyzed 2 CE-based tools (CTI and MCI) and 2 LCA-based tools (SMM Prioritization Tools and SLCA) and compared them with the remaining KIF dimensions. These analytical frameworks and tools help companies to assess products on their circularity using different indicators. 3 of those tools: CTI, MCI, and SLCA covered 5 of the 7 remaining KIF dimensions: *Effect on Circularity, Social Impacts, Enabling Technologies, Tier 2 and 3 Requirements, and Value Chain Synergies*. The remaining KIF dimensions: *State of Development and Scale Requirements* might require sources other than frameworks and tools. For example, when conducting my KIF analysis of plastic and glass packaging, I used industry reports and news articles. Lastly, it’s important for these tools to evolve to better meet circularity needs. CE-based tools like CTI and MCI can evolve to include environmental and social impacts, whereas LCA-based tools like the SMM can involve include metrics such as material loops.

Although the CE-based tools had some gaps in their circularity analysis, they inspire innovation since they stem from at least one of the CE Schools of Thought. Questions for practitioners, designers, and engineers help to rethink the way resources are extracted, products are produced, and materials are reentered back into the supply chain. These tools give a different perspective to view end-of-life products as “materials” rather than “waste”. What some tools might lack in quantitative metrics for measurement, they make up for with qualitative principles and pathways.

The innovative products of the future will not be inspired by using backwards-thinking tools, but forward-thinking ones. Therefore, I propose the following modifications to the LCA and KIF:

The LCA can be better suited for circularity by transforming its 4 phases:

- Goal and Scope: Aim to measure for circularity and set the scope to cradle-to-grave so the entire supply chain is in focus.
- Inventory Analysis: Look at sustainable inputs (i.e. recycled materials, solar energy, reclaimed water) and outputs (i.e. material by-products, captured methane, carbon sequestration)

- Impact Assessment: Include impacts normally excluded (i.e. impacts to human safety, impacts from material leakage to the environment, impacts on the local economy)
- Interpretation: Have more transparency (i.e. how inventory waste data was collected/used, limitations on material capture at all stages in the supply chain)

The KIF can also evolve with time by separating out its 12 dimensions to include more specific material streams (i.e. formal vs informal waste diversion percentages, kg of waste leakage vs kg of overall waste to landfill/environment).

Summary of Findings:

- There is no single CE-based or LCA-based tool that covers all the CE dimensions in the KIF
- When performing a CE assessment on a product, a CE framework (i.e. the KIF) can cover more dimensions of circularity when paired with both LCA-based (i.e. SLCA) and CE-based (i.e. CTI) analytical tools that use both qualitative and quantitative data.
- The LCA is not well-suited to answer questions of circularity, and need to be reconceived to meet more worthy CE-based tool, including topics such as: product development, circularity loops, social impacts, recycling technologies, company environmental performance, scale requirements, and value chain synergies.

REFERENCES

About Us. (n.d.). Gallo Glass. https://www.galloglass.com/

Acquisition of Anchor Glass by Ardagh Group. (n.d.). Ardagh Group. https://www.ardaghgroup.com/news-centre/acquisition-of-anchor-glass-by-ardagh-group

All About Polypropylene (PP): Production, Price, Market & its Properties. (n.d.). Plastics Insight. https://www.plasticsinsight.com/resin-intelligence/resin-prices/polypropylene/

Annual Review 2019. (2020, Feb 27). Nestlé. https://www.Nestlé.com/sites/default/files/2020-03/2019-annual-review-en.pdf

Ardagh Group Annual Report. (2019, December 31). United States Securities and Exchange Commission. https://www.ardaghgroup.com/userfiles/files/investors/Ardagh-Group-SA-Annual-Report-2019-full.pdf

Ayres, R. (2016). *Energy, complexity and wealth maximization*. Cham?] Switzerland: Springer.

Bellis, M. (2019, May 25). *A brief history of the invention of plastics*. ThoughtCo. https://www.thoughtco.com/history-of-plastics-1992322

Benefits of Glass Packaging. (n.d.). Glass Packaging Institute. https://www.gpi.org/benefits-of-glass-packaging

Benyus, J. (2002). *Biomimicry: Innovation inspired by nature*. New York: Perennial.

Braungart, Michael, & McDonough, William. (2009). *Cradle to cradle: Remaking the way we make things*. London: Vintage.

Chasan, E. (2019 September 25). *There's Finally a Way to Recycle the Plastic in Shampoo and Yogurt Packaging*. Bloomberg. https://www.bloomberg.com/news/features/2019-09-25/polypropylene-plastic-can-finally-be-recycled

Circular Transition Indicators Case Studies. (2020 January). WBCSD. https://s3.eu-central-1.amazonaws.com/ctitool.com/CTI+Case+Studies.pdf

Circular Transition Indicators V1.0. (2020 January). WBCSD.

https://www.wbcsd.org/contentwbc/download/8240/127985

Comparative Plastics Industry Manufacturing Operating Costs. (2017). The Boyd Company, Inc. https://pennsnortheast.com/images/uploads/PNE_Boyd_Plastics_Industry_Cost_Report_060617.pdf

Cradle to Cradle Certified Product Standard Version 3.1. (2016). Cradle to Cradle. https://s3.amazonaws.com/c2c-website/resources/certification/standard/STD_C2CCertified_ProductStandard_V3.1_082318.pdf

Custom Food Packaging Solutions. (n.d.). Placon. https://www.placon.com/wp-content/uploads/2019/03/Placon_Custom_Food_Containers.pdf

Dean, Jeff. (2019, July 19). *The Brutal Reality of Being the World's 'Best' Recycler*. Global Recycler. https://globalrecycler.com/the-brutal-reality-of-being-the-worlds-best-recycler/

Deschamps, J., Simon, B., Tagnit-Hamou, A., & Amor, B. (2018). Is open-loop recycling the lowest preference in a circular economy? Answering through LCA of glass powder in concrete. *Journal of Cleaner Production*, 185, 14–22. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.03.021

DMK Group acquires German based baby food brand Alete. (2019, April 2). Food Business Africa. https://www.foodbusinessafrica.com/2019/04/02/dmk-group-acquires-german-based-baby-food-brand-alete/

Environmental Overview Complete Life Cycle Assessment of North American Container Glass. (2010). Glass Packaging Institute. https://assets.noviams.com/novi-file-uploads/gpi/pdfs-and-documents/Learn_About_Glass/N-American_Glass_Container_LCA.pdf

Ferrão, P., Ribeiro, P., Rodrigues, J., Marques, A., Preto, M., Amaral, M., … Costa, e I. (2014). Environmental, economic and social costs and benefits of a packaging waste management system: A Portuguese case study. Resources, Conservation and Recycling, 85, 67–78. https://doi.org/https://doi.org/10.1016/j.resconrec.2013.10.020

First Self-Assessment Framework to Measure Business' Circular Performance Launched by WBCSD and 26 Companies. (2020, January 21). PR Newswire. http://search.proquest.com/docview/2342749391/

Geissdoerfer, Martin, et al. “The Circular Economy – A New Sustainability Paradigm?” *Journal of Cleaner Production*, vol. 143, 21 Dec. 2016, pp. 757–768., doi:10.1016/j.jclepro.2016.12.048

Gërxhani, K. (2004). The Informal Sector in Developed and Less Developed Countries: A Literature Survey. *Public Choice*, 120(3), 267-300. *Glass Containers Manufacturing Process*. (n.d.). Oberk. https://www.oberk.com/packaging-crash-course/packaging-resource-guide/glass-containers-manufacturing-process

Glass Facts. (n.d.). Glass Packaging Institute. http://www.gpi.org/recycling/glass-recycling-facts

Glass Manufacturing. (n.d.). Glass Packaging Institute. https://www.gpi.org/glass-manufacturing

Glass: Material-Specific Data. (n.d.). United States Environmental Protection Agency. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data

Glass Recycling- Current Market Trends (2018, May). Recovery Worldwide. https://www.recovery-worldwide.com/en/artikel/glass-recycling-current-market-trends_3248774.html

Global Glass Recycling Market Report. (2019, April 4). Absolute Reports. https://www.absolutereports.com/TOC/14108575#Companies

Global 100 Most Sustainable Corporations. (2016). Ranking the Brands. https://www.rankingthebrands.com/The-Brand-Rankings.aspx?rankingID=107&year=1020

Graedel, Thomas, & Allenby, Braden R. (2010). *Industrial ecology and sustainable engineering*. Upper Saddle River, NJ: Prentice Hall

GreenBiz 17 Tutorial Slides: "Transformative Organizational Success through Leadership". (2017, Feb 28). Slide Share. https://www.slideshare.net/GreenBiz/greenbiz-17-tutorial-slides-transformative-organizational-success-through-leadership

Gue, I., Ubando, A., Cuello, J., & Culaba, A. (2018). Assessing Microalgal Biodiesel Sustainability via MCI and LCA Frameworks. *2018 IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM), 1–5.* https://doi.org/10.1109/HNICEM.2018.8666405

Hawken, Paul, Lovins, Amory B., & Lovins, L. Hunter. (1999). *Natural capitalism: Creating the next industrial revolution* (1st ed.). New York: Little, Brown & Company.

Hosseinijou, S., Mansour, S., & Shirazi, M. (2014). Social life cycle assessment for material selection: a case study of building materials. The International Journal of Life Cycle Assessment, 19(3), 620–645. https://doi.org/10.1007/s11367-013-0658-1

How to Certify. (n.d.). Cradle to Cradle Certified. https://www.c2ccertified.org/get-certified/product-certification-process

Humbert, S., Rossi, V., Margni, M., Jolliet, O., & Loerincik, Y. (2009). Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots. *The International Journal of Life Cycle Assessment*, *14*(2), 95–106. https://doi.org/10.1007/s11367-008-0052-6

ISO 14040:2006 Environmental Management: Life Cycle Assessment Principles and Framework; International Organization for Standardization (ISO): Geneva, 2006

ISO 14044:2006 Environmental Management: Life Cycle Assessment Requirements and Guidelines; International Organization for Standardization (ISO): Geneva, 2006

Kimani, A. (2020, April 19). *How The COVID-19 Plastic Boom Could Save The Oil Industry*. https://oilprice.com/Energy/Energy-General/How-The-COVID-19-Plastic-Boom-Could-Save-The-Oil-Industry.html

Levy, M. (2017). Life Cycle Analysis-Strengths and Limitations of LCA. In *Encyclopedia of Sustainable Technologies* (pp. 233-236). Elsevier.

Life Cycle Analysis- Reducing our footprint, one step at a time. (n.d.). Nespresso. https://www.Nestlé-nespresso.com/newsandfeatures/life-cycle-analysis-reducing-our-footprint

Life Cycle Impacts of Plastic Packaging Compared to Substitutes in the United States and Canada. (2018 April). American Chemistry. https://plastics.americanchemistry.com/Reports-and-Publications/LCA-of-Plastic-Packaging-Compared-to-Substitutes.pdf

Lyle, John T.(1994). *Regenerative Design for Sustainable Development*. New York: John Wiley.

Lyons, S. (2019). *Is a substitute for plastic coming anytime soon?: Cutting down on the* *plastics you use, particularly single-use plastics, is a great idea, but there's probably always going to be a need for some plastics in our world.* Ultimo: Australian Broadcasting Corporation. Retrieved from http://login.ezproxy1.lib.asu.edu/login?url=https://search-proquest-com.ezproxy1.lib.asu.edu/docview/2310451300?accountid=4485

Lonca, G., Muggéo, R., Imbeault-Tétreault, H., Bernard, S., & Margni, M. (2018). Does material circularity rhyme with environmental efficiency? Case studies on used tires. *Journal of Cleaner Production*, 183, 424–435. https://doi.org/10.1016/j.jclepro.2018.02.108

McKinney, L. A. (2014). Foreign direct investment, development, and overshoot. *Social Science Research*, *47*, 121–133. https://doi.org/10.1016/j.ssresearch.2014.04.003

Mission. (n.d.). The Kaiteki Institute. http://www.kaiteki-institute.com/english/

NaturNes. (n.d.). Nestlé. https://www.Nestlé.com/brands/allbrands/naturnes

Nestlé to invest €1.68 billion in sustainable packaging. (2020, January). Packaging Europe. https://packagingeurope.com/Nestlé-sustainability-pledge/

New Life Cycle Assessment Proves Industry Success in Reducing Environmental Footprint. (2017, February 13). European Container Glass Federation. https://feve.org/new-life-cycle-assessment-proves-industry-success-reducing-environmental-footprint/

Niero, M., & Hauschild, M. Z. (2017). *Closing the Loop for Packaging: Finding a Framework to Operationalize Circular Economy Strategies*. Procedia CIRP, 61, 685–690. https://doi.org/https://doi.org/10.1016/j.procir.2016.11.209

Non-Technical Case Studies. (2015, May 8). Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Non-Technical-Case-Studies_May2015.pdf

North, E. J., & Halden, R. U. (2013). Plastics and environmental health: the road ahead, *Reviews on Environmental Health*, *28*(1), 1-8. doi: https://doi.org/10.1515/reveh-2012-0030

Overview of Greenhouse Gases. (n.d.). United States Environmental Protection Agency. https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Pauli, G. (2015). *The Blue Economy Version 2.0: 200 Projects Implemented; US$ 4 Billion Invested; 3 Million Jobs Created*. Academic Foundation.

Peters, T., & Peters, T. (2011). Nature as Measure: The Biomimicry Guild. *Architectural Design*, 81(6), 44–47. https://doi.org/10.1002/ad.1318

Plastic Containers and Packaging. (n.d.). United States Environmental Protection Agency. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/containers-and-packaging-product-specific-data#PlasticC&P

Products from Alete. (n.d.). German Deli Store. https://germandelistore.com/alete/

Raise your Glasses. (2018, October 5). Siemens. https://new.siemens.com/global/en/company/stories/industry/raise-your-glasses.html

Rigamonti, L., Falbo, A., Zampori, L., & Sala, S. (2017). Supporting a transition towards sustainable circular economy: sensitivity analysis for the interpretation of LCA for the recovery of electric and electronic waste. *The International Journal of Life Cycle Assessment*, *22*(8), 1278–1287. https://doi.org/10.1007/s11367-016-1231-5

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, *207*, 542–559. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.014

Schools of Thought. (n.d.). Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/circular-economy/concept/schools-of-thought

Stahel, W. (2016). The Circular Economy. *Nature,* 531(7595), 435–438. https://doi.org/10.1038/531435a

Stahel, W. (2010). *The Performance Economy* (2nd ed.). Basingstoke, England; New York: Palgrave Macmillan.

Sustainable Packaging Unwrapped (2019, April 10). Global Web Index. https://1ec4c04de36c11011b7b-b0e482557560956b9f71038ee7452dfa.ssl.cf3.rackcdn.com/Sustainable-Packaging-Unwrapped.pdf

(Thanos) Bourtsalas, A. C., Zhang, J., Castaldi, M. J., & Themelis, N. J. (2018). Use of non-recycled plastics and paper as alternative fuel in cement production. *Journal of Cleaner Production*, 181, 8–16. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.01.214

The New Plastics Economy. (2016, January 19). Ellen MacArthur Foundation.

https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics

The Price Tag of Plastic Pollution. (2019). Deloitte. [pdf]. https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/strategy-analytics-and-ma/deloitte-nl-strategy-analytics-and-ma-the-price-tag-of-plastic-pollution.pdf

Towards the Circular Economy, Vol. 1. (2013). Ellen MacArthur Foundation. [pdf]. https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

Umair, S., Björklund, A., & Petersen, E. E. (2015). Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. *Resources, Conservation and Recycling*, 95, 46–57. https://doi.org/https://doi.org/10.1016/j.resconrec.2014.11.008

UNEP-SETAC, Benoît C, Mazijn B (ed) (2009) *Guidelines for social life cycle assessment of products*. UNEP, Paris. http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf

United States National Postconsumer Plastic Bottle Recycling Report. (2018). American Chemistry Council. https://plastics.americanchemistry.com/Reports-and-Publications/2018-National-Post-Consumer-Plastics-Bottle-Recycling-Report.pdf

User Manual for the Sustainable Materials Management Prioritization Tools. (2002 February). U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2020-02/documents/user_manual_for_smm_prioritization_tools.pdf

Vo, L. & Jiang, J. (2013, June 19). *Video: How A Used Bottle Becomes A New Bottle, In 6 GIFS*. NPR. https://www.npr.org/sections/money/2013/06/11/190668206/how-a-used-bottle-becomes-a-new-bottle-in-6-gifs

Ward, C. P., Armstrong, C. J., Walsh, A. N., Jackson, J. H., & Reddy, C. M. (2019). Sunlight Converts Polystyrene to Carbon Dioxide and Dissolved Organic Carbon. *Environmental Science & Technology Letters*, *0*(0), null. https://doi.org/10.1021/acs.estlett.9b00532

What is the Great Pacific Garbage Patch? (n.d.). The Ocean Cleanup. https://theoceancleanup.com/great-pacific-garbage-patch/

Woodhouse, K.M. (2014). After Earth Day: The Modern Environmental Movement.

Reviews in American History 42(3), 556-563. doi:10.1353/rah.2014.0074

Zapico, J., Brandt, N., & Turpeinen, M. (2010). Environmental Metrics. *Journal of Industrial Ecology*, 14(5), 703–706. https://doi.org/10.1111/j.1530-9290.2010.00272.x