Rethinking Design for Sustainability: A Novel Multi-Objective Optimization Methodology for Sustainable Product Lifecycle Design

[1]Yan-Ruei Huang, M.S., [2]Ching-Pin Tung, Phd

[1] International Degree Program in Climate Change and Sustainable Development, National Taiwan University

[2] Bio-environmental System Engineering, National Taiwan University

Introduction

This study explores the management and enhancement of product sustainability across multiple objectives and metrics from a comprehensive Life Cycle Assessment (LCA) perspective. To examine this issue, three subsidiary research questions are proposed:

01 **How can product sustainability be effectively managed and improved across different lifecycle stages within LCA framework?**

02 **How can multi-objective optimization methods be employed to simultaneously manage multiple sustainability objectives in product design?**

03 **How can the proposed methodology facilitate the practical implementation of sustainable product design?**

Methods

To address the aforementioned research questions, this study is conducted using the following methods:

01 **Propose a multi-objective sustainable product lifecycle management methodology aimed at improving product sustainability.** (As shown in Fig. 1.)

02 **Implement an industrial case study to demonstrate how sustainable product design and decision-making processes can be strengthened by applying the proposed methodology**

03 **Conduct an interview with industrial partners to deepen our understanding of the applicability and practicality of the proposed methodology.**

Step 1	Step 2	Step 3	Step 4
Identifying potential product design pathways	*Assessing sustainability of potential design pathways*	*Formulating a sustainable product design optimization model*	*Solving the optimization problem*

Fig. 1. Proposed Methodology for Multi-Objective Sustainable Product Lifecycle Management

Industrial Case Study

- ***Case study scenario:***
  - Taiwan's annual boba tea consumption exceeds 1 billion cups, equating to more than 46 cups per national annually
  - Describe how to design different beverage packaging lifecycle stages to enhance sustainability
- ***Objectives:***
  - Total Lifecycle cost, TLC (unit: NTD)
  - Global warning potential, GWP (unit: kg CO2 eq)
  - Toxicity (unit: kg 1,4-DB eq)
    - Human toxicity
    - Marine aquatic toxicity
    - Terrestrial toxicity
    - Fresh water aquatic toxicity
- ***Data sources:***
  - Ecoinvent
  - Taiwan Ministry of Environment
  - Industry collaboration partners
- ***Fig. 2 illustrates the potential design pathways of beverage packaging in Taiwan***

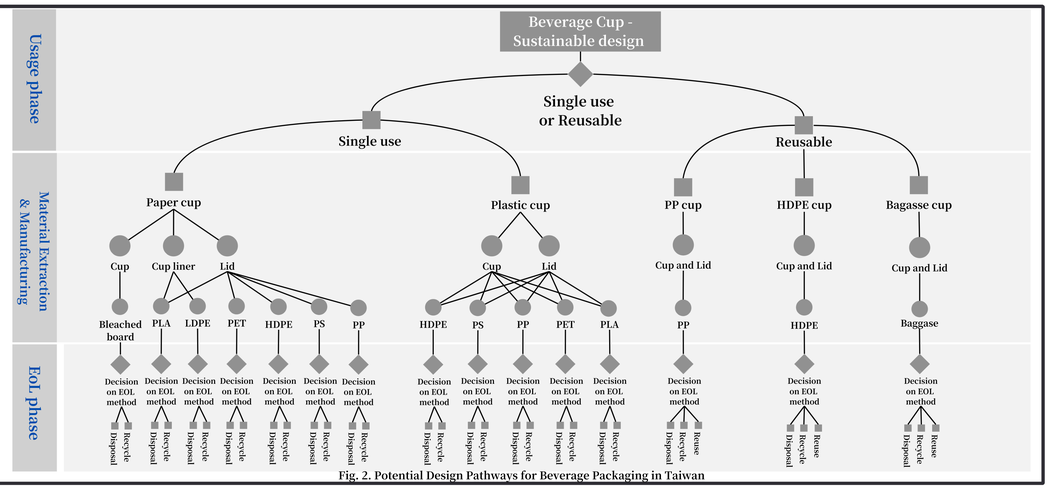

Fig. 2. Potential Design Pathways for Beverage Packaging in Taiwan

Implementation Results

- Fig. 3 illustrates the resulting 3-dimensional Pareto optimal solutions and Pareto frontier with respect to TLC, GWP, and Toxicity objectives (from different perspective).
- Highlighting 29 various optimal beverage packaging designs with corresponding weighting of each objective, named from case 1 to 29

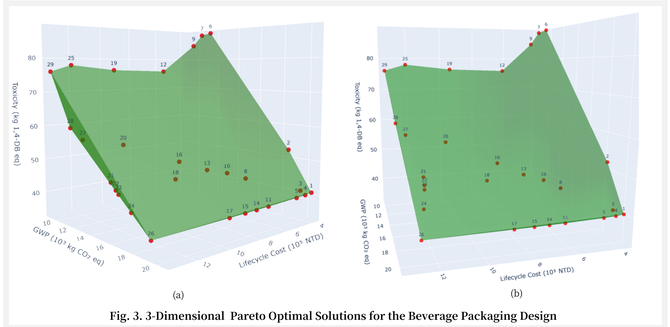

Fig. 3. 3-Dimensional Pareto Optimal Solutions for the Beverage Packaging Design

- Fig. 4 illustrates the relationships between each pair of objectives using 2-dimensional charts.
- ***Trade-off relationship between objectives***
  - Fig. 4 (a) highlights the trade-off between TLC and GWP, indicating that higher TLC leads to significantly lower GWP.
  - Fig. 4 (b) demonstrates that increasing TLC results in lower toxicity levels.
  - Fig. 4 (c) reveals a crucial phenomenon in this case study: GWP and Toxicity performances are often not bundled .
- ***Knee point in 2-dimensional pareto frontier***
  - In Fig. 4(a) the knee point occurs around case 12, showing that investments in GWP reduction are more efficient to the left of this point than to the right.

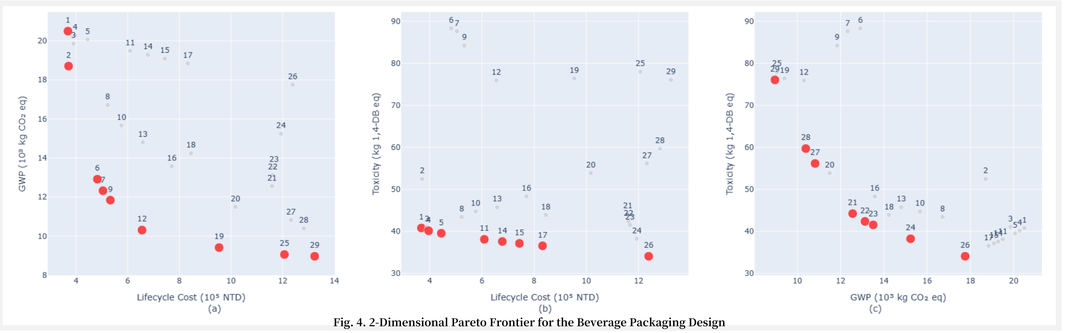

Fig. 4. 2-Dimensional Pareto Frontier for the Beverage Packaging Design

Interview insight

01 Noted that once the Pareto frontier was reached, the final decision significantly depended on each organization's prioritization of the sustainability objectives.

02 Knee points allow organizations and policymakers to clearly comprehend the relationship between sustainability investments and the corresponding returns in performance.

03 Proposed methodlogy aligns closely with existing industry practices, LCA, thus reducing potential implementation barriers

04 Potential challenges in data collection, as many organizations might not systematically track sustainability related data

Author Information

- Name: ***Yan Ruei (Ray) Huang***
- ***Actively pursuing PhD opportunities***
- *Master student at National Taiwan University*
- Research Focus: ***Life Cycle Optimization, LCA, Multi-objective Decision Making, Circular Economy***
- Contact Info: ***R12247006@ntu.edu.tw***