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An Integrated Holistic Approach Toward Sustainable Product Design Using Life Cycle Assessment

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Introduction

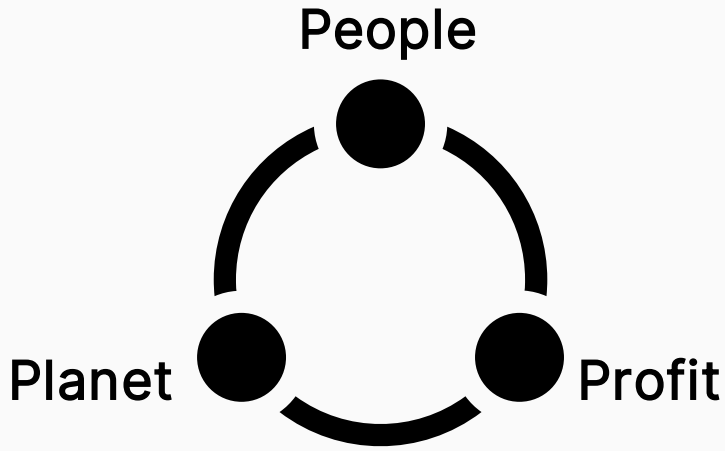
- “Triple Bottom Line” is a holistic approach where a product is sustainable in terms of environment, economy, and society. (Elkington, 1997)

- Sustainable Product Design: “The ability of a product to work continuously while ensuring lowest environmental impacts and providing economic and social benefits to the stakeholders.”

  (Ahmad et al. 2018)

- Design phase influences ~80% of a product's sustainability impacts.

  (Kulantunga et al. 2015, Lewis et al. 2017)



Motivation and Objective

- Current challenges:
  - There are numerous tools and methods available
  - Many methods apply to specific products or life cycle phases
  - Absence of a holistic approach

- Research Objective: To integrate change propagation and design for sustainability (DfS) methods to simultaneously consider design parameters and sustainability impacts using a reusable water bottle as a case study.

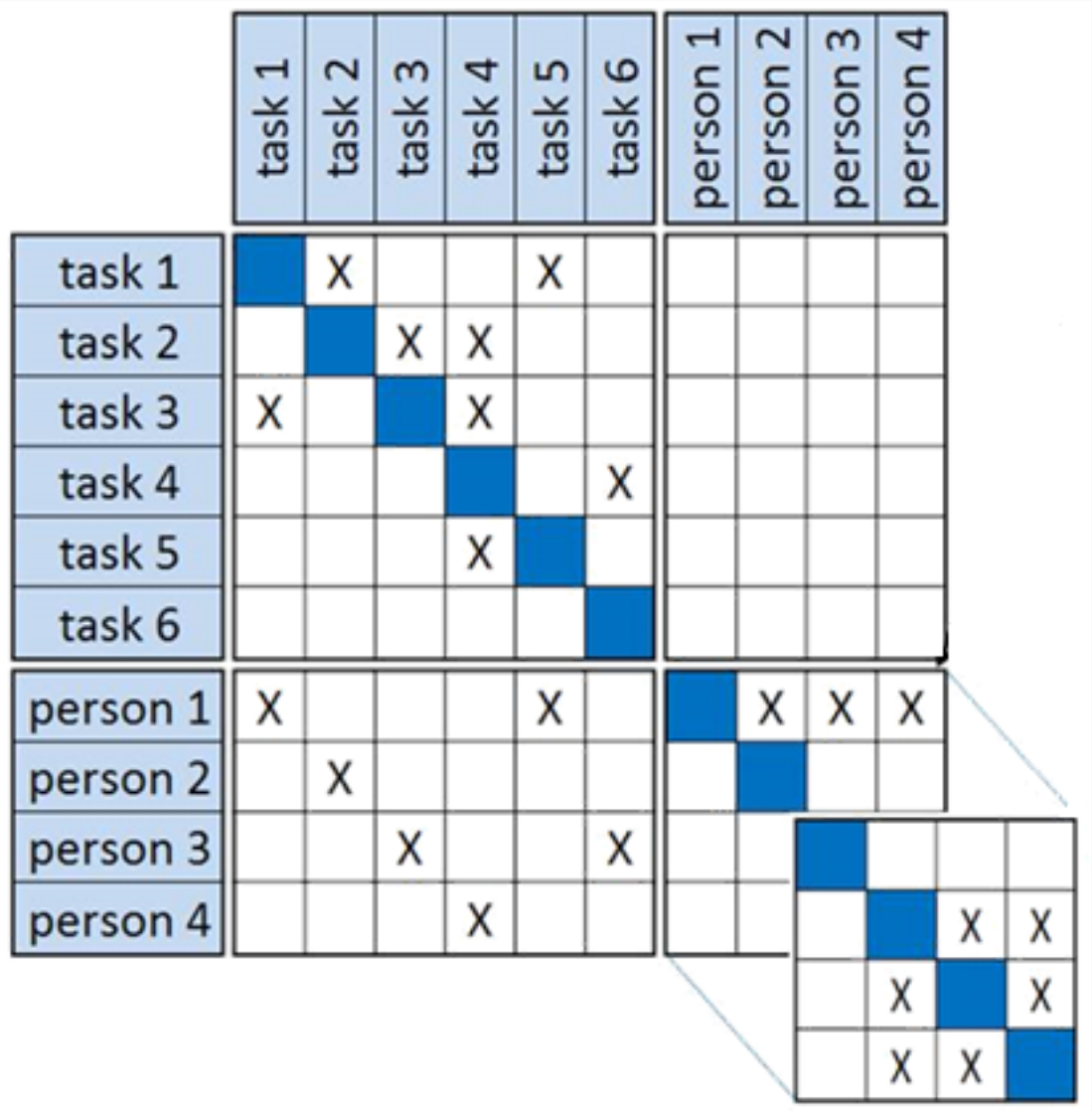
- Research Questions:
  1. How do changes in design parameters of a reusable water bottle impact environmental, social and economic sustainability?
  2. What critical design decisions/parameters can be optimized considering the social, economic and environmental impacts?

Multi-Domain Matrix (MDM)

- Design Structure Matrix (DSM)
- Common tool to demonstrate and analyze design change propagation

  (Brahma et al. 2023)
- Highly compact and scalable method of representing the systems

  (Eppinger and Browning, 2012)
- Cross-domain DSMs are MDM



Multi-Domain Matrix (DSM.org)

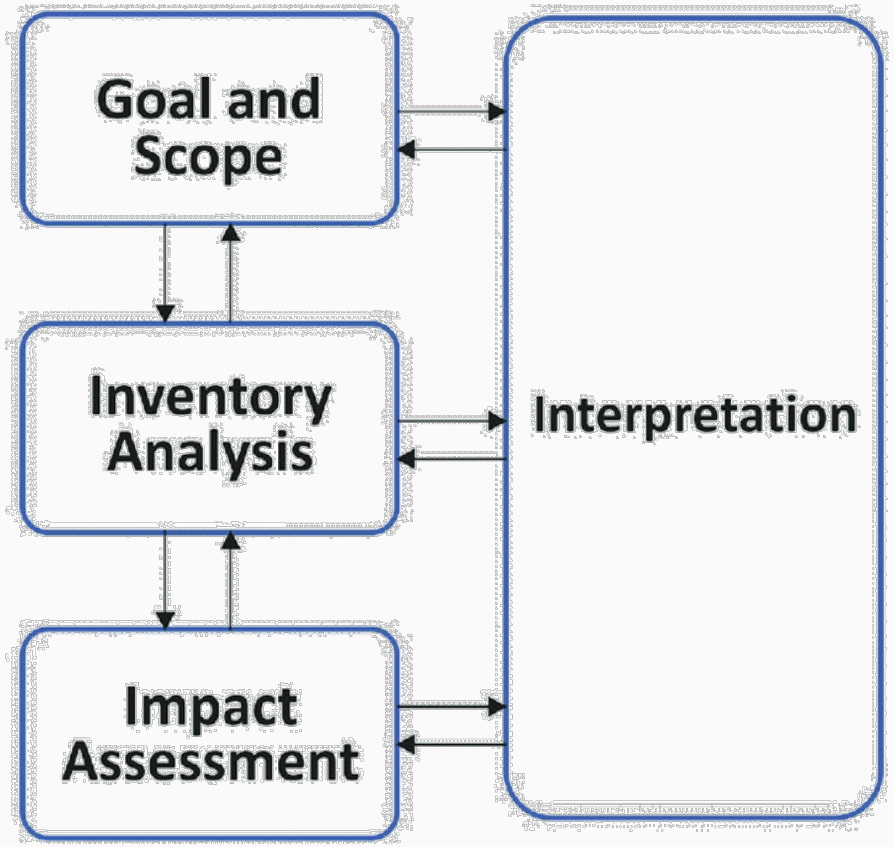
Life Cycle Assessment (LCA)

- Evaluates the potential environmental impacts of products throughout their entire lifecycle

  (ISO, 2006)

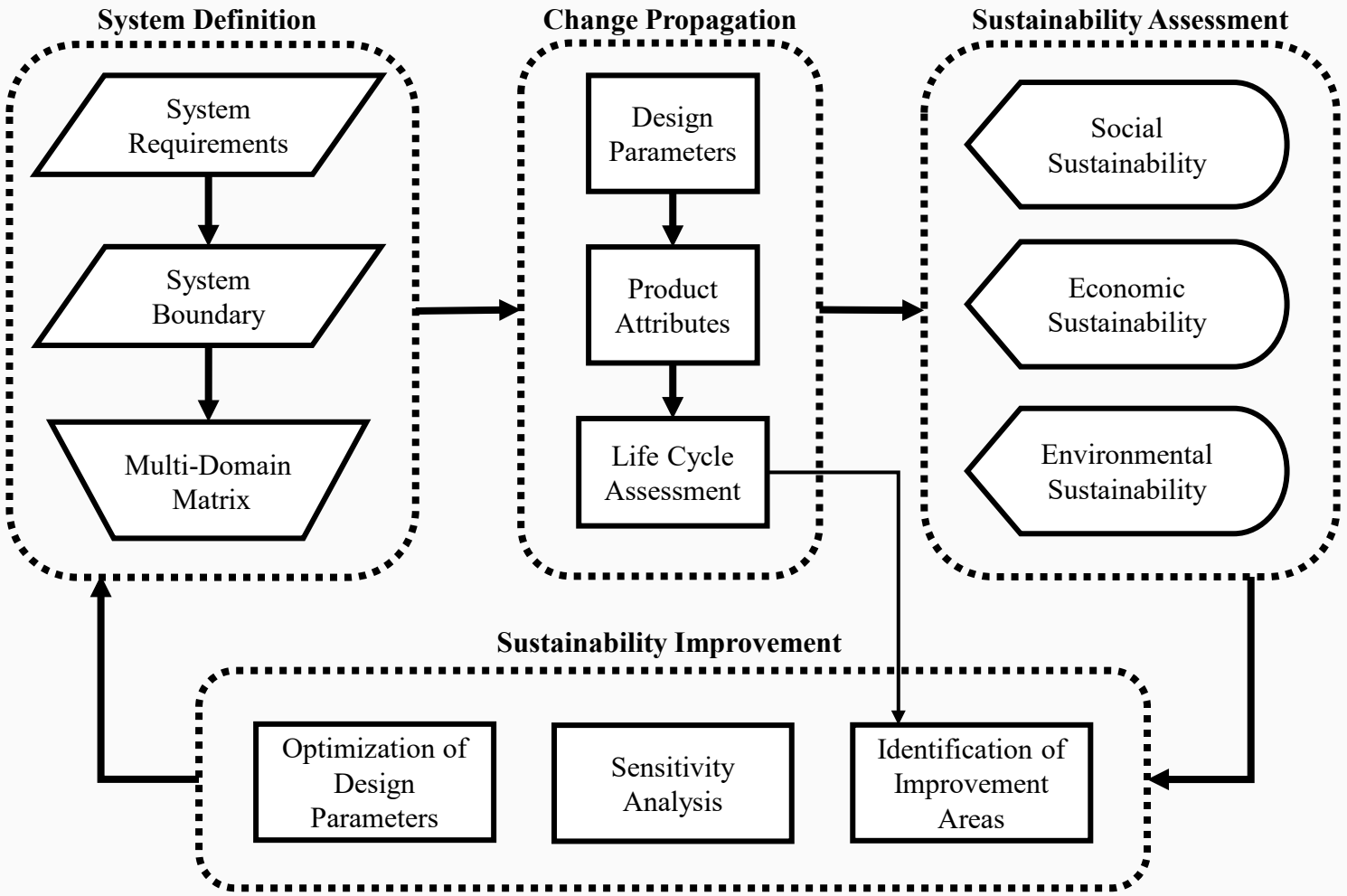
- LCA Procedure:
  - Defining goal and scope
  - Life cycle inventory (LCI)
  - Life cycle impact assessment (LCIA)
  - Interpretation

- LCI – Ecoinvent
- LCIA – ReCiPe 2016 (Huijbregts et al. 2016)



LCA framework (ISO 14040)

Methodology



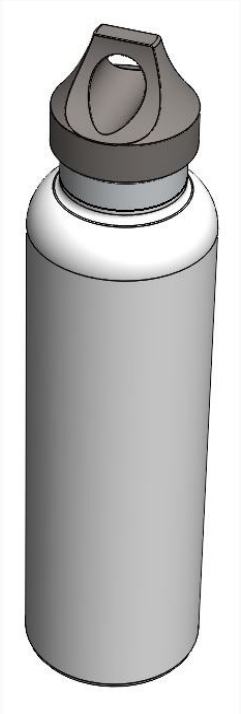
Case Study

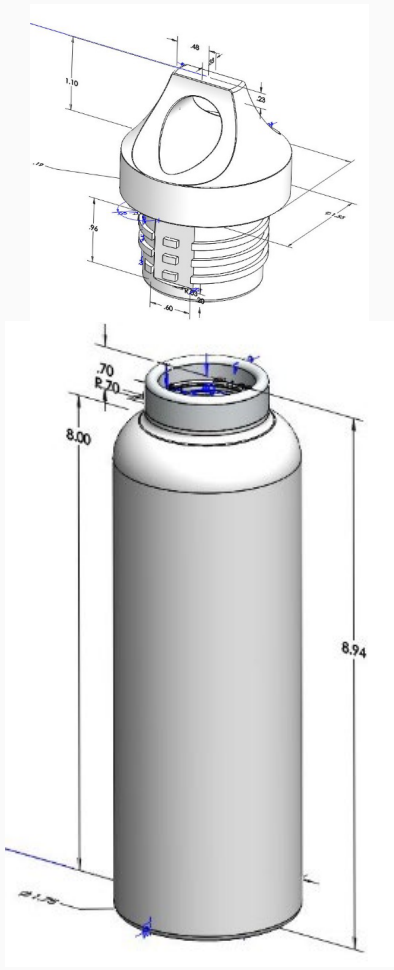
Reusable Water Bottle

- Simple mechanism
- Consumer-based product

- Three components:
  - Cap (polypropylene plastic resin)
  - Seal (silicone rubber)
  - Bottle (Stainless Steel 304)

- Different manufacturing processes:
  - Steel Production
  - Powder Coating
  - Injection Molding

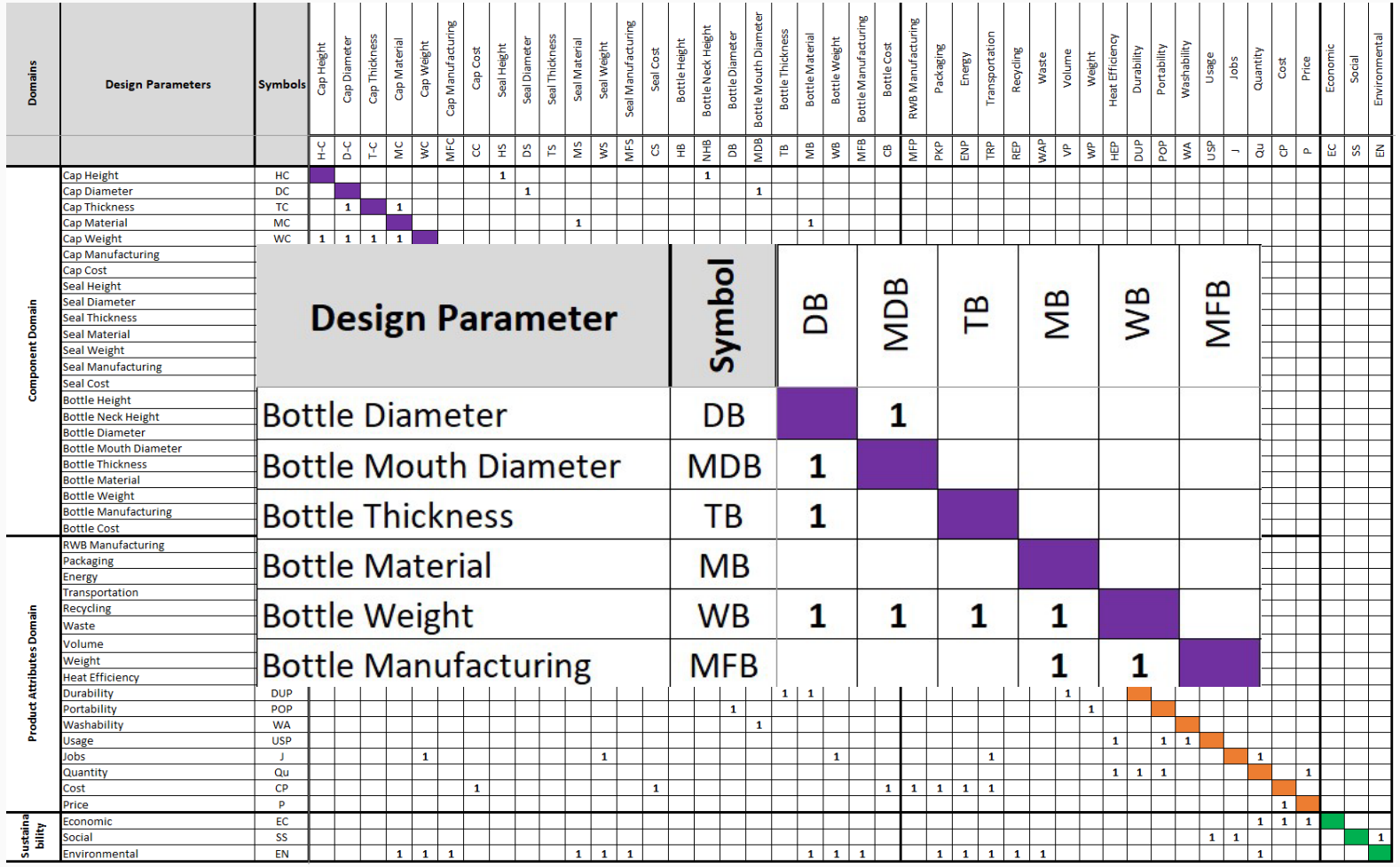




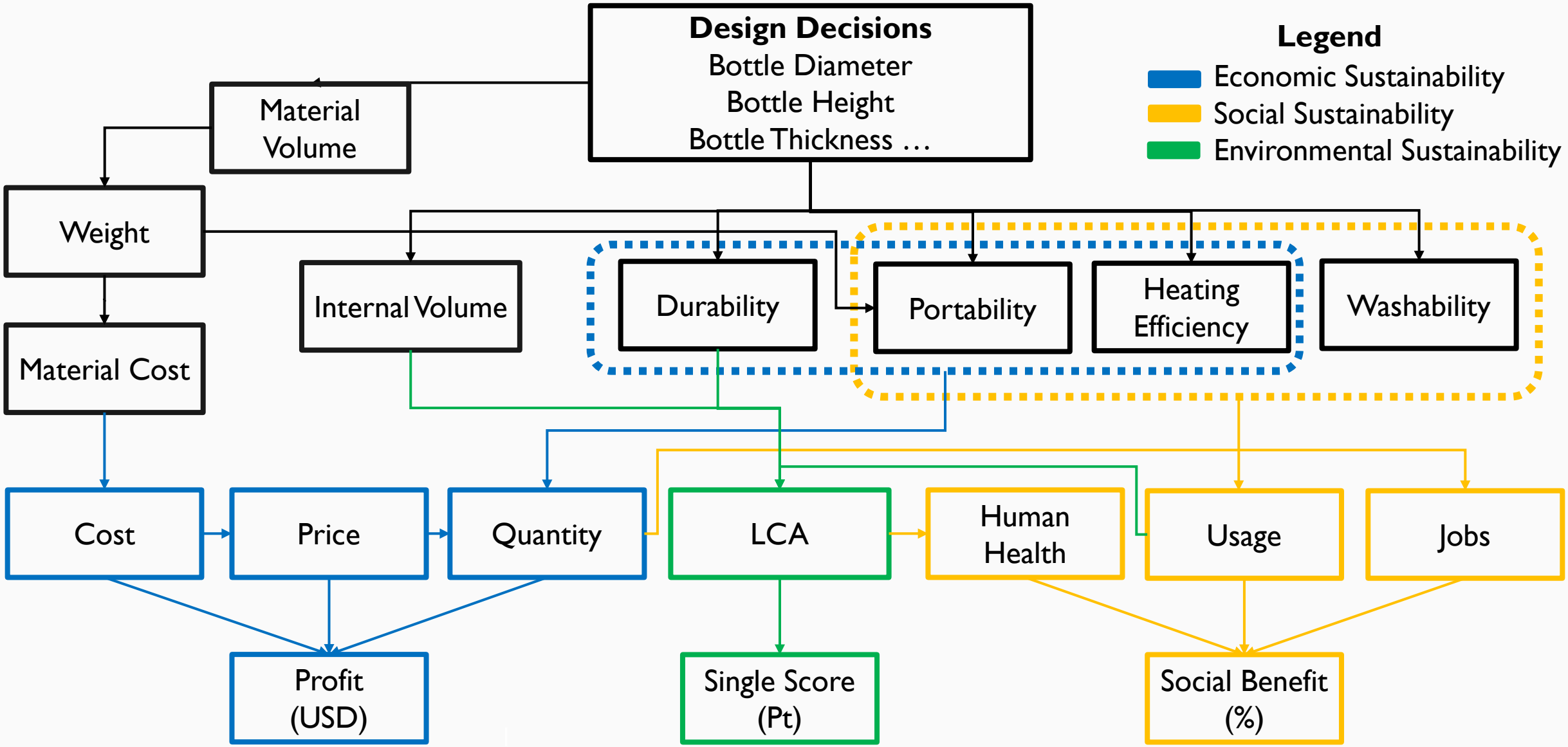
Change Propagation

Multi-domain Matrix (MDM)

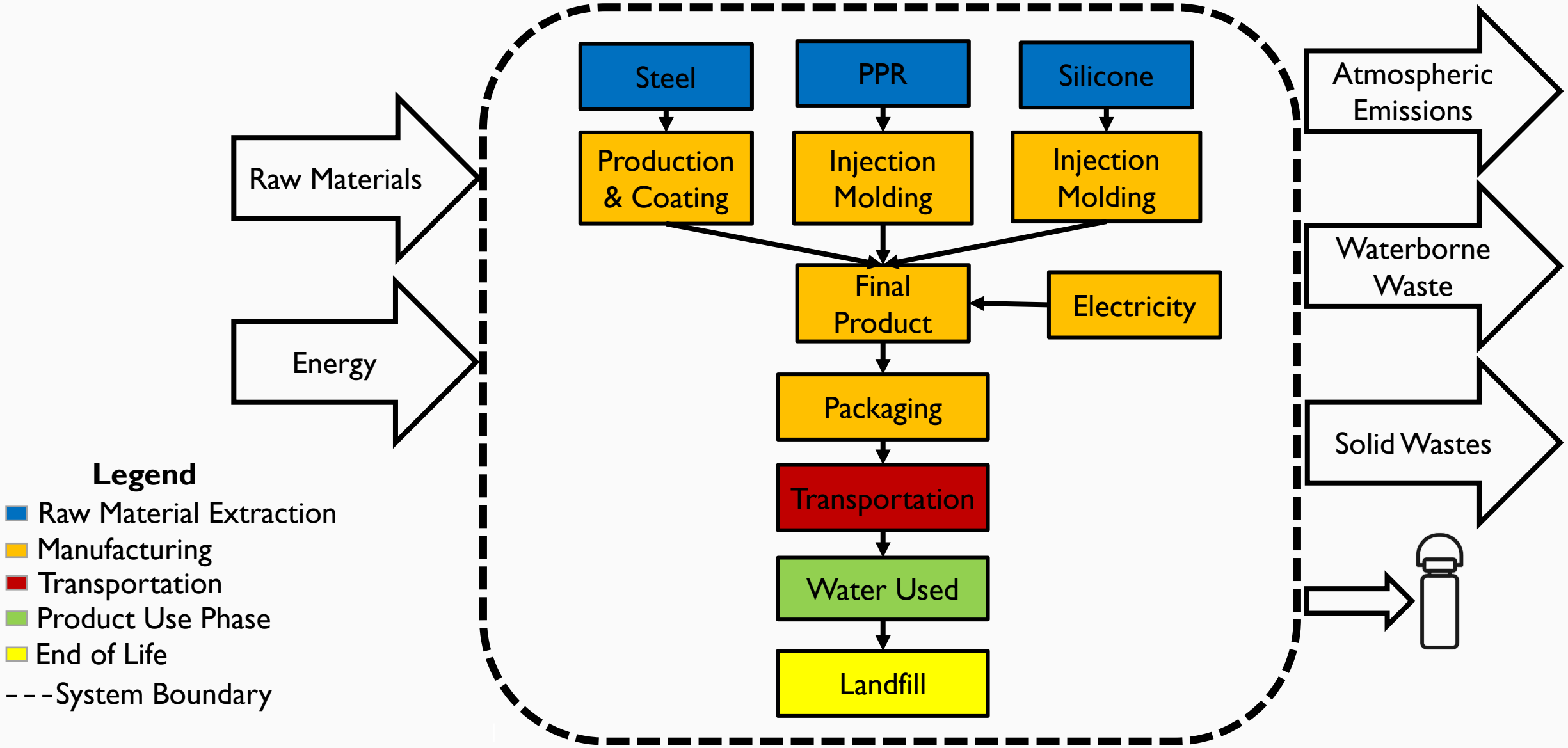
- Component Domain
  - Dimensions
  - Material
- Product Attributes Domain
  - Volume
  - Weight
  - Portability
  - Durability
  - Quantity
  - Usage
  - Cost
- Total 43 Parameters



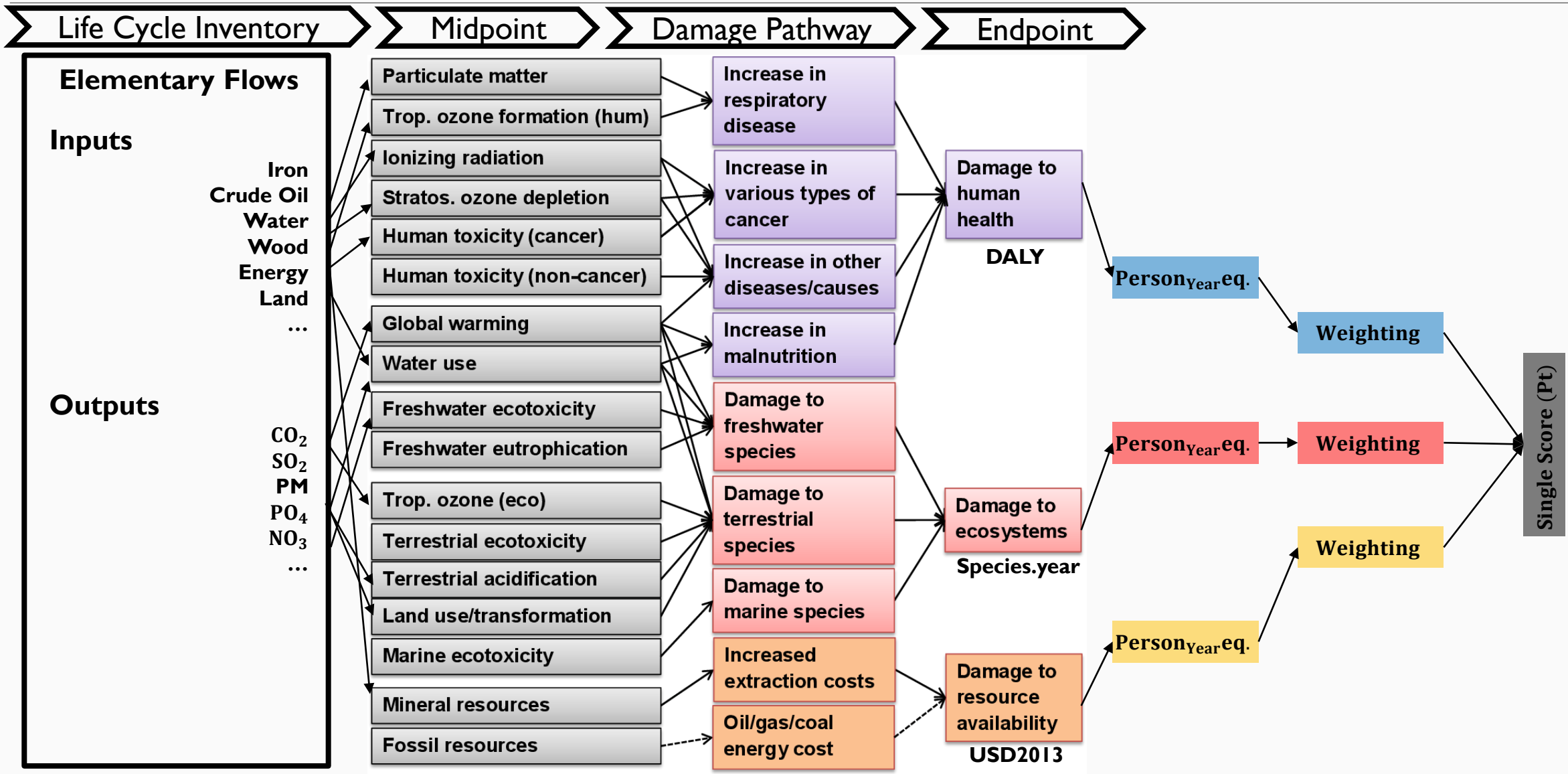
Calculation Flow



Product System Description



Life Cycle Impact Assessment (LCIA) – ReCiPe 2016 (H)



Sustainability Assessment

Baseline results of Reusable Water Bottle

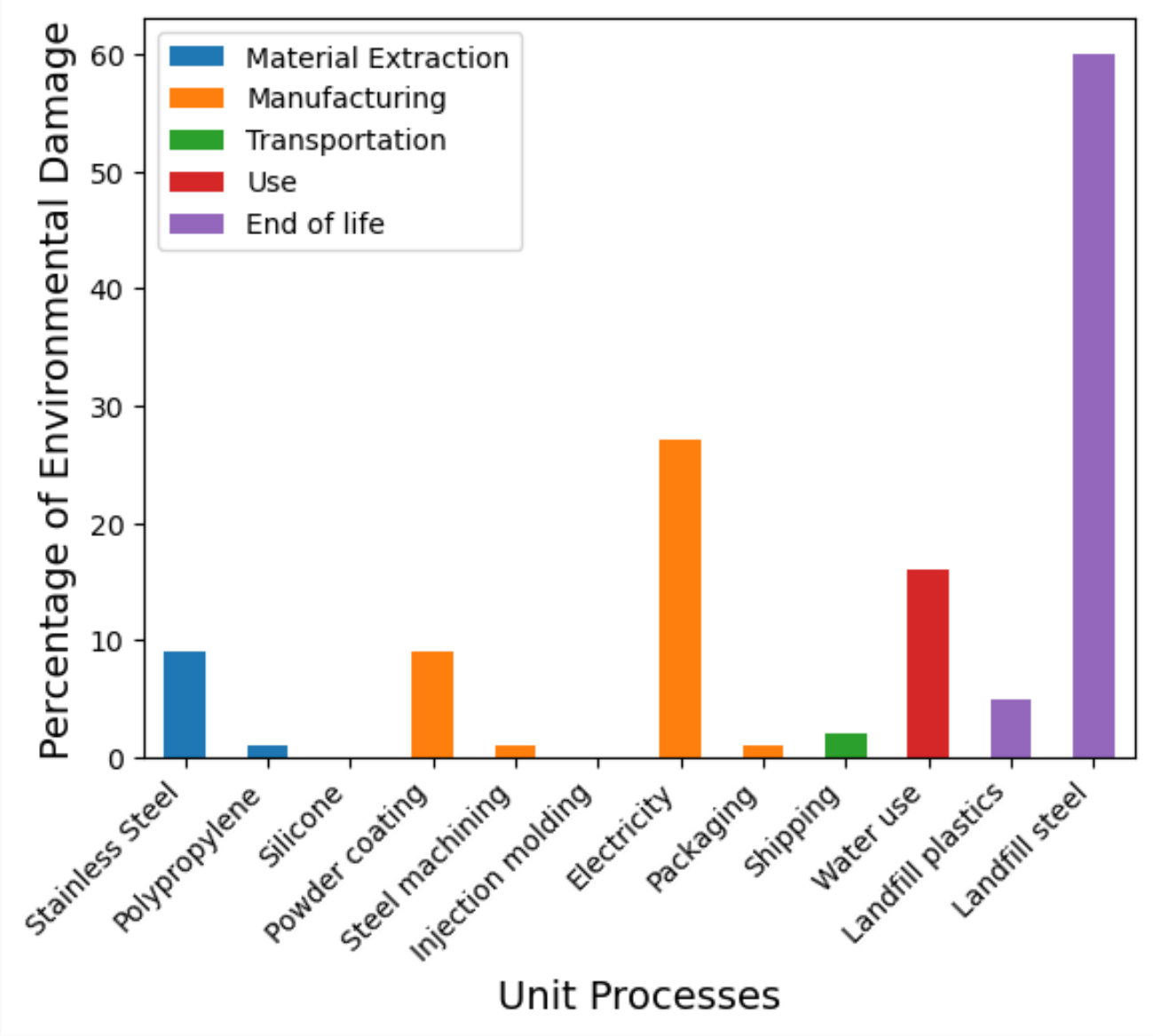
Sustainability dimension	Metric	Value
Environmental	Single Score (mPt)	9.06
Social	Social Metric (%)	38
Economic	Profit (USD)	466,881

Most significant midpoint category for each endpoint

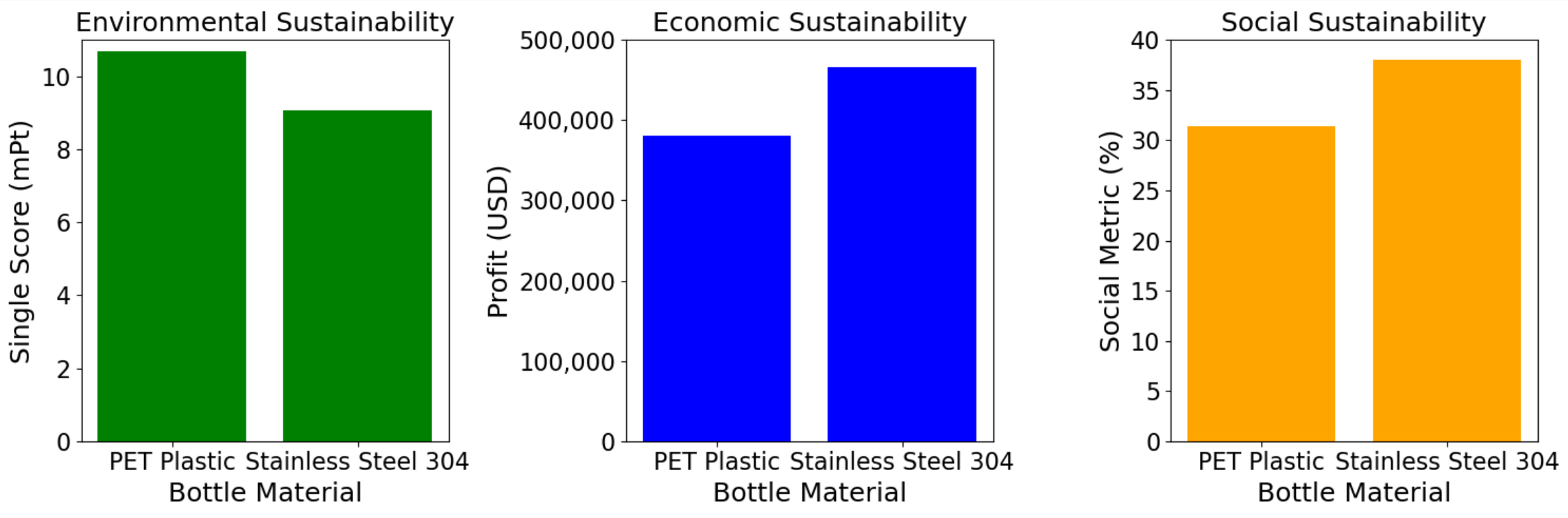
Endpoint	Total value	Most significant midpoint
Damage to Resource availability	3.03E-3 USD2013	Mineral resource scarcity
Damage to Human health	7.49E-06 DALY	Global warming
Damage to Ecosystems	1.51E-8 species.yr	Global warming

- Most significant unit process contributing to these midpoint categories is stainless steel

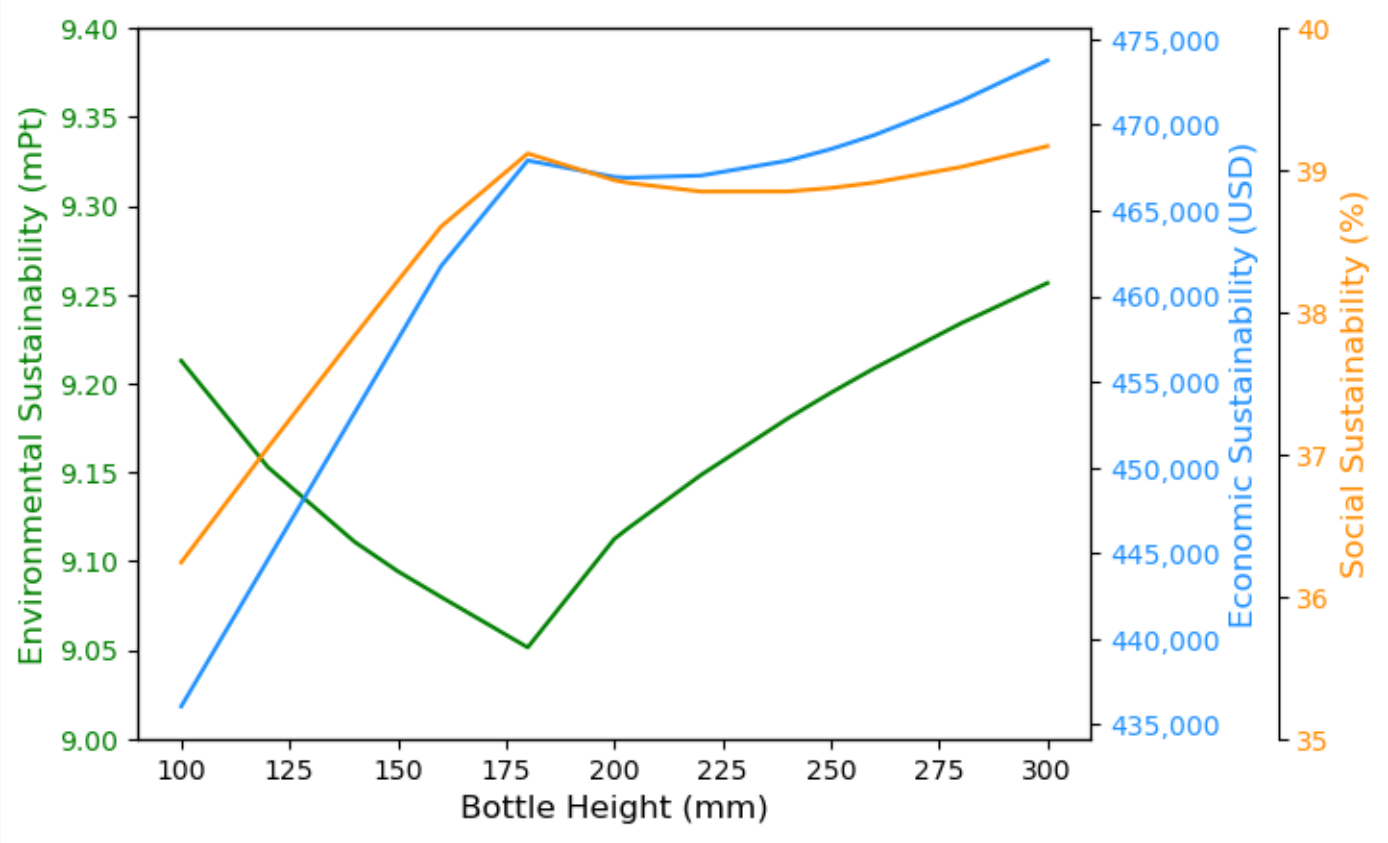
Sustainability Assessment



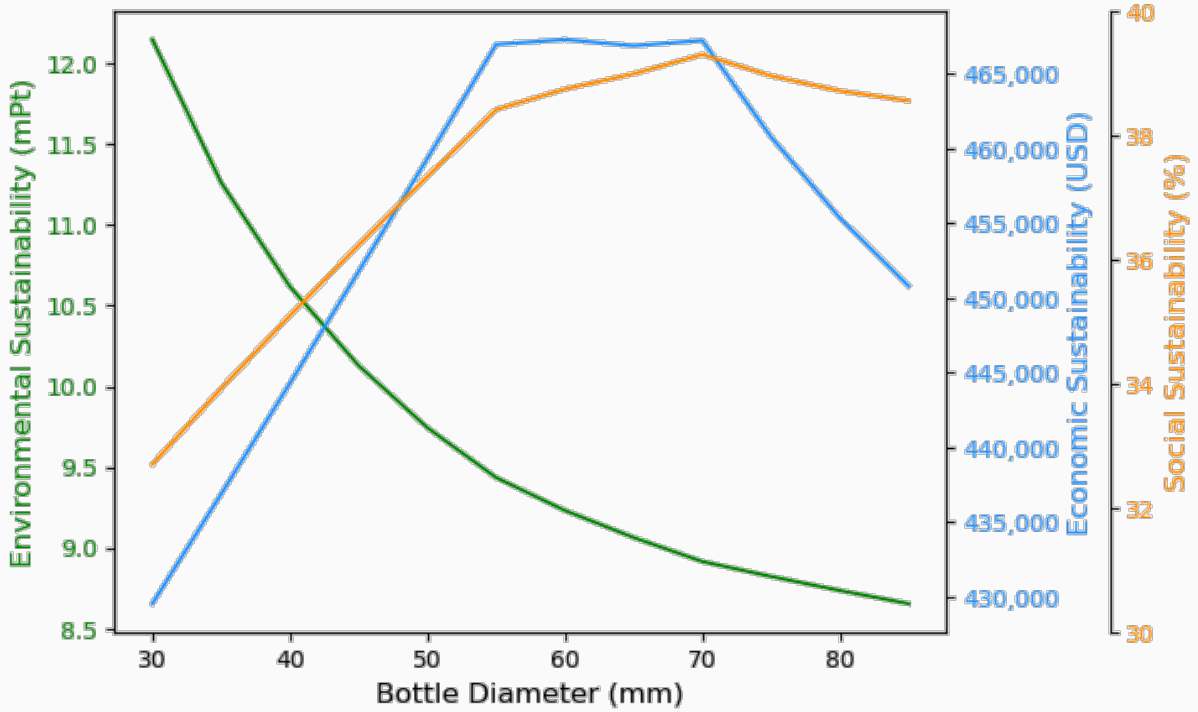
Changing the Bottle Material

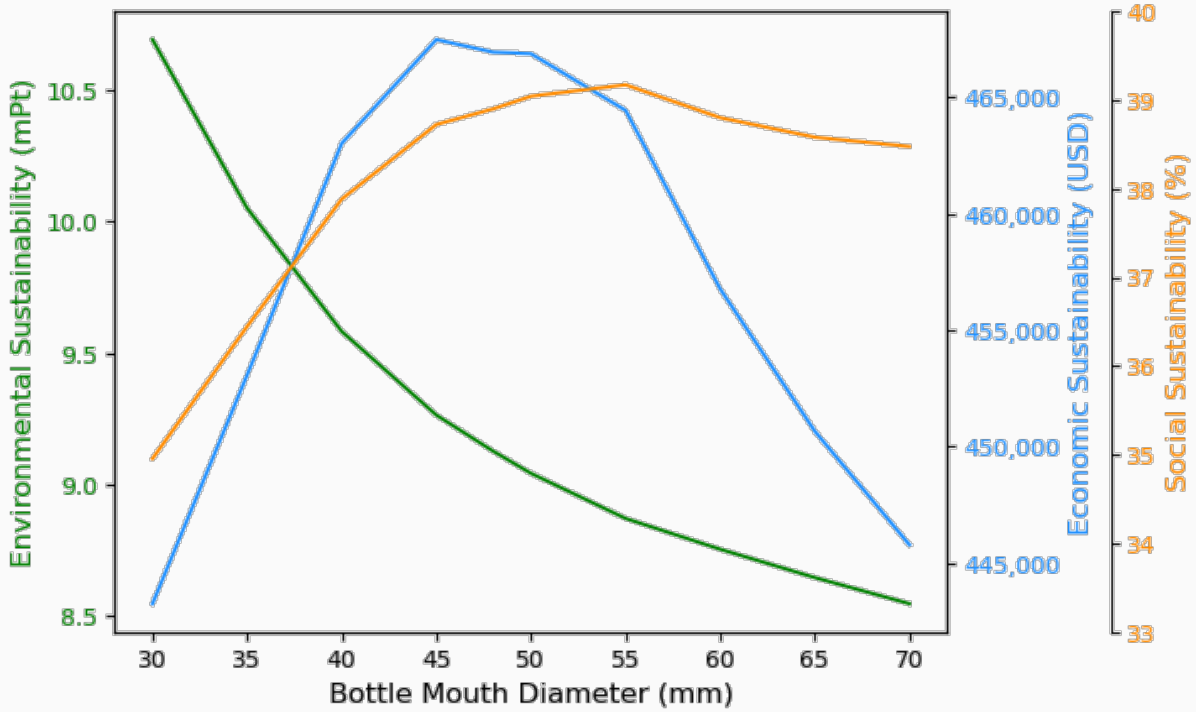


Sensitivity Analysis



Sensitivity Analysis





Conclusion

- Successful integration of change propagation (MDM) and LCA, enabling design space exploration while simultaneously considering all sustainability metrics.
- In-depth analysis of sustainability impacts provided by sensitivity analysis.
- Enabling comparison by simultaneous consideration of design decisions impacts on sustainability.
- Iterative process for all design parameters to balance these sustainability metrics.

Next Steps

- Applying this framework to a more complex product(s) – Aerospace systems
- Considering the design requirements sustainability impacts
- Improving different aspects of the framework

  - Change propagation:
    - Clustering algorithms applied to unfold more details
    - Automation of MDM generation

  - Life Cycle Assessment:
    - Uncertainty analysis of LCA data
    - Adding allocation methods

  - Sustainability Improvement
    - Considering wider range of social and economic impacts
    - Enabling optimization within the framework

References

- Elkington, J., 1997. Cannibals with Forks: The Triple Bottom Line of 21st Century Business. Capstone, Oxford.
- Ahmad, S., Wong, K. Y., Tseng, M. L., and Wong, W. P., 2018. “Sustainable product design and development: A review of tools, applications and research prospects”. Resources, Conservation and Recycling, 132, pp. 49–61.
- Lewis, H., Gertsakis, J., Grant, T., Morelli, N., and Sweatman, A., 2017. Design+ environment: a global guide todesigning greener goods. Routledge.
- Kulatunga, A., Karunatilake, N., Weerasinghe, N., and Ihalawatta, R., 2015. “Sustainable manufacturing-based decision support model for product design and development process”. Procedia CIRP, 26, pp. 87–92.
- Brahma, A., and Wynn, D. C., 2023. “Concepts of change propagation analysis in engineering design”. Research in Engineering Design, 34(1), pp. 117–151
- Eppinger, S. D., and Browning, T. R., 2012. Design structure matrix methods and applications. MIT press.
- Multiple-domain matrix (MDM). The Design Structure Matrix (DSM). (2019, April 25). https://dsmweb.org/multiple-domain-matrix-mdm/
- ISO, 2006. Environmental management: life cycle assessment; requirements and guidelines, Vol. 14044. ISO Geneva, Switzerland
- Ecoinvent, 2023. ecoinvent database. Online, https://ecoinvent.org. Accessed 22 January 2023.
- Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Hollander, A., Zijp, M., an van Zelm, R., 2016. Recipe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report: characterization. Tech. rep., National Institute for Public Health and the Environment.

Thank you

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