

# Superstructure as a Communication Tool in Pre-Emptive Life Cycle Design Engaging Society: Findings from Case Studies on Battery Chemicals, Plastics, and Regional Resources

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## ABSTRACT

Emerging technologies require sophisticated design and optimization due to their rapid advancement and potential to alter material flows and life cycles. However, their future development remains uncertain due to sociotechnical factors such as regulations, infrastructure, and market dynamics. Multiple technologies are often considered simultaneously, but their interactions and synergies are not systematically evaluated. This study addresses pre-emptive life cycle design in social challenges by integrating emerging technologies into superstructures, which help visualize alternative candidates for design problems. Case studies on battery chemistry, plastics, and regional resource circulation demonstrate this approach. For battery technology, nickel-manganese-cobalt lithium batteries have dominated over lithium iron phosphate alternatives. Superstructures were developed to assess recycling technologies and were refined through communication with managers of Japanese national battery projects. In plastics, system designs integrating biomass-derived and recycled carbon sources were explored, and scenario planning with life cycle assessment (LCA) was shared with stakeholders. Regional resource circulation was studied through technological integration and local stakeholder engagement, leading to demonstration tests. Findings suggest that superstructures and technology assessments enhance understanding of applicable technologies and their trade-offs. Given the critical role of social acceptance in technology implementation, computer-aided process engineering (CAPE) tools should facilitate discussions on socio-technical and socio-economic aspects of process systems engineering.

**Keywords:** Life cycle assessment, Co-creation, Scenario planning, Social engagement, Policy making

## INTRODUCTION

The rapid advancement of emerging technologies

[1] necessitates a comprehensive approach to their design and optimization, incorporating considerations of social systems and regulatory frameworks. These

technologies possess the potential to transform material flows and life cycles; however, their future development remains highly uncertain due to the evolving sociotechnical landscape, including regulatory policies, societal infrastructure, and market dynamics [2]. The concurrent exploration of multiple technological solutions for a given challenge further complicates the assessment of their respective boundaries and potential synergistic interactions. A systematic evaluation framework is, therefore, imperative to ensure the effective integration of emerging technologies into optimized systems.

In this study, we address the pre-emptive life cycle design (LCD) of emerging technologies within the context of societal challenges, focusing on case studies in battery chemistry, plastics, and regional resource management. To achieve this, we construct comprehensive frameworks that encapsulate a range of technological alternatives and facilitate the visualization of potential design pathways by superstructures. These superstructures, developed in collaboration with industrial stakeholders and national initiatives, serve as the basis for modeling life cycle scenarios using life cycle assessment (LCA) methodologies.

## MATERIALS AND METHODS

### Framework Development of Pre-Emptive LCD

Pre-emptive LCD requires the steps of process systems engineering, e.g., alternative generation, analysis, evaluation and optimization, and sensitivity analysis. Forward-looking LCA has become an important tool for examining the future applicability of emerging technologies considering the scenarios in line with shared socioeconomic pathways [3]. New technologies are constantly being developed, and while they may solve one particular problem, they can also cause other problems, which can have a complex impact on the processing system. In this situation, it can be effective to use superstructure-based visualization to support communication while implementing forward-looking LCA and designing the life cycle, while proposing appropriate alternative solutions.

In the case study described below, we conducted pre-emptive LCD based on the individual problems and conditions. The extracted works and functions of pre-emptive LCD are framed and visualized as a model represented in integrated definition type 0 modeling language (IDEF0) [4].

### Case Examples of Pre-Emptive LCD

In the alternative generation of pre-emptive LCDs, we consider not only technology candidates that have reached a certain level of technological maturity, as evidenced by patents and academic papers, but also cutting-edge technological development issues that are

currently being addressed in national projects. Even for technology candidates with low technological maturity, it is possible to consider the impact on the life cycle in advance using future LCA combined with computer-aided process engineering (CAPE) [3]. This makes it possible to design the life cycle appropriately, taking into account resource recycling, environmental impact, socio-economics, and socio-technical regimes. At this time, it is important to consider the elements of the life cycle other than the target technology, even in projects that are developing elemental technology, and there is a possibility that an appropriate evaluation range and purpose can be set by building a superstructure.

The superstructure in this study encompasses all potential pathways in cradle-to-grave life cycles of target functions. Concerning the cases below, both technological options and socio-economic/technical options could influence the future performance of these life cycles. Wherever possible, such options were gathered from national projects, experts, and relevant government officials.

### Circulation of battery chemicals

In the realm of battery chemistry, nickel-manganese-cobalt (NMC) lithium-ion batteries (LiB) have emerged as the dominant technology, although lithium iron phosphate (LFP) batteries remain a viable alternative. Superstructures were formulated to evaluate recycling technologies, incorporating insights from Japanese national battery technology initiatives [5]. The required data was obtained from industries and authorized LCA databases. The mathematical models from the previous studies [5] were applied.

### Plastic life cycles with renewable carbon sources

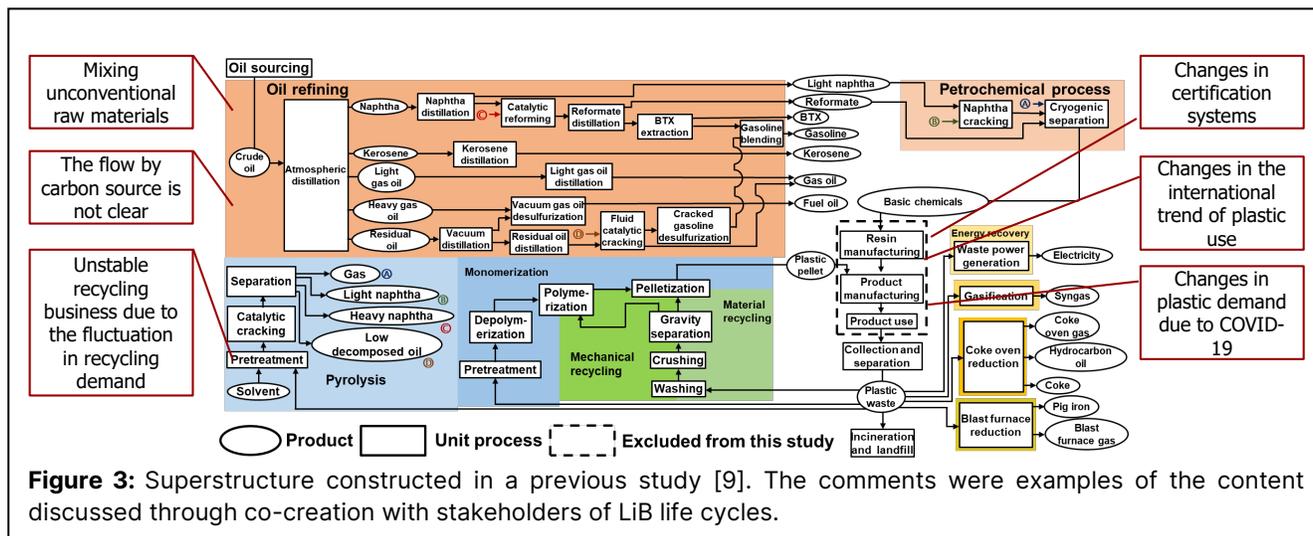
In the plastics sector, the transition to biomass-derived and recycled carbon sources necessitates systematic design considerations. Scenario planning and LCA based on superstructure-based analyses were conducted and shared with stakeholders to inform sustainable carbon strategies [6, 7]. The required data was obtained from industries and authorized LCA databases. The mathematical models from the previous studies [9] were applied. The social situation was obtained from surveys, e.g., on bioplastics [9].

### Circulated use of regionally available resources

A shift from imported fossil fuels to local renewable resources and empowering rural areas is crucial for regional sustainability. Regionally available resources, e.g., biomass from agriculture and forestry, renewables such as solar and wind, and wastes to be treated, have been examined with technologies for their valorization. In this regard, however, not individual use but combined application of such regional resources is effective [10]. Superstructure-based analysis supported by technology







### Findings in Regional Systems Case

Tanegashima hosts a diverse range of agricultural, forestry, and livestock industries, with sugarcane cultivation playing a central role in regional culture and economy. The sugar industry, which processes locally grown sugarcane into raw sugar, is a key economic driver. Historically, sugarcane bagasse has been utilized as fuel within sugar mills, but previous studies indicate that the available bagasse-derived energy exceeds the demand for sugar production, presenting an underutilized resource [14]. Additionally, the island's forests suffer from aging tree populations and a low proportion of high-quality timber suitable for sawmilling. Expanding the use of woody biomass for energy could simultaneously reduce reliance on fossil fuels and improve forest health [15]. Industrial symbiosis is emerging as a transformative strategy for fostering fossil-free resource utilization in agricultural and forestry regions. The combined application of bagasse and woody biomass has the potential to serve as a stable biomass feedstock for fuel production via torrefaction [16]. Furthermore, advances in sugarcane cultivar breeding could enhance industrial sustainability, as confirmed by rigorous assessments of potential impacts on sugar production [17].

Based on such regional problems and conditions, the superstructure of regional-resource circulated systems was proposed [10, 18] and used for the co-creation with regional stakeholders. Regional residents may not have a comprehensive understanding of the potential of the regional resources, and it can be said that they were motivated by the possibility of simultaneously achieving regional revitalization, de-fossilization, and green transformation. At the same time, we also found that clarifying the challenges that require reform also creates friction regarding the details.

### CONCLUSION

The findings of this study highlight the critical role of superstructure-based technology assessments in facilitating a comprehensive understanding of technological feasibility, trade-offs, and viable implementation pathways. As technological adoption is intrinsically influenced by social acceptance, it is imperative that computer-aided process engineering (CAPE) tools are designed to integrate sociotechnical and socio-economic dimensions within process systems engineering frameworks. By embedding these considerations, CAPE can enhance decision-making processes, promote stakeholder engagement, and support the development of sustainable and resilient technological solutions. This interdisciplinary approach is essential for advancing the practical implementation of emerging technologies in complex industrial and regional systems.

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