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COMPETITIVE NET-ZERO: A SIMULTANEOUS ENGINEERING APPROACH TO SUSTAINABLE PRODUCT DEVELOPMENT AND MANUFACTURING

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Abstract

The European industrial landscape is undergoing a transformation driven by the dual imperatives of achieving net-zero emissions and ensuring resource efficiency, as outlined in the EU's Net-Zero Industry Act and Critical Raw Materials Act. These regulations mandate the development of net-zero technologies within the EU and the establishment of a circular economy to enhance technological competitiveness and reduce reliance on third countries. The growing demand for 'Made in Europe' products, characterized by high quality, cost-effectiveness, and sustainability, presents a multi-centric design challenge that requires integrating innovative development strategies into engineering practice. This paper advocates the adoption of Simultaneous Engineering in product design, emphasizing the parallel development of products and their manufacturing processes to improve manufacturability, cost-effectiveness, and quality while reducing time to market. It explores methods such as Robust Design and Tolerance Design to effectively manage risk and uncertainty during development and addresses the challenge of multi-centric optimization through the Design for Excellence (DfX) paradigm, which allows for the simultaneous consideration of multiple performance criteria. Finally, it highlights the need to re-evaluate engineering education, advocating for the integration of these methodologies as core competencies to equip future engineers for the challenges of a rapidly changing industry on the path to competitive net-zero.

Key words: *Robust Design, Tolerance Design, Sustainable Product Development, Design for Excellence (DfX), Simultaneous Engineering*

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1. Introduction

The *European Union* has set ambitious goals for the green transformation of its society, economy, and industry, with the aim of achieving net-zero emissions and enhancing sustainability across all sectors. Central to this strategy are legislative measures such as the Net Zero Industry Act and the Critical Raw Materials Act, which establish targets for the production of at least 40% of net-zero technologies, including batteries, wind power, and hydrogen, within the EU by 2030 (European Commission, 2023a, 2023b). These policies seek to reduce reliance on imports from third countries and strengthen the European value chain through competitive mass production and circular economy practices.

A key element of this transformation is the shift from linear production models to a circular economy, which aims to extend product lifecycles and recover valuable resources through strategies such as reuse, remanufacturing, and recycling (Potting et al., 2017). Early-stage product design plays a pivotal role in this transition, as decisions made during the initial design phases can significantly impact a product's environmental footprint and material efficiency (Babbitt et al., 2021). This paper demonstrates how specific design methodologies, including Tolerance Design, Robust Design, and Design for Circularity, can address key challenges in sustainable product development and manufacturing. Two use cases illustrate how these methodologies can be practically applied to enhance competitiveness and support circularity goals in the context of net-zero technologies.

2. Literature Review: Sustainable Product Development

Early-stage product design is crucial in shaping a product's environmental footprint, material use, and overall lifecycle management. Decisions made during this phase can determine a significant portion of a product's environmental impact, as highlighted by (Babbitt et al., 2021; Diaz et al., 2021). This chapter explores the methodologies of Design for Manufacturing (DfM) and Design for Disassembly (DfD), which together form a comprehensive approach to Sustainable Product Development (SPD).

2.1 Design for Manufacturing: Managing Variability and Ensuring Robustness

Design for Manufacturing focuses on optimizing product development for efficient, high-quality manufacturing processes. It includes methodologies like Robust Design and Tolerance Design, which help manage variability and uncertainty in production. Robust Design aims to create products that are less sensitive to variability, whether from manufacturing inconsistencies or environmental fluctuations (Goetz et al., 2020). By addressing these factors early in the design process, products can be made to perform consistently under various conditions, thus minimizing costly iterations later.

Tolerance Design, as discussed by (Morse et al., 2018), plays a crucial role in managing dimensional variations, setting geometric parameters, and specifying tolerance limits to ensure products meet functional requirements. Early integration of tolerancing into the design phase links product design with manufacturing processes, reducing rework and improving overall product quality. This integration aligns with the principles of Simultaneous Engineering, where the simultaneous development of products and processes enables more efficient and predictable production.

2.2 Design for Disassembly: Enabling Circular Economy Strategies

As Europe transitions towards a circular economy, Design for Disassembly (DfD) has emerged as a key methodology for supporting sustainable lifecycle management. The R-strategies framework (Potting et al., 2017), which includes actions like Refuse, Reduce, Reuse, and Recycle, provides a structured approach to prioritizing circularity during the design process. While traditional design practices often neglect circularity, this framework emphasizes strategies that extend product lifecycles and enhance resource recovery (Babbitt et al., 2021).

Implementing DfD principles enables products to be easily disassembled for repair, refurbishment, or recycling, facilitating higher levels of material recovery. However, as noted by (Schlögl et al., 2024), the use of complex joining techniques such as welding and adhesives can complicate non-destructive disassembly, limiting circularity potential. Overcoming these challenges requires integrating circularity considerations into the design process from the outset, as (Shahbazi & Jönbrink, 2020) suggest, by using design guidelines that make products more modular and durable.

2.3 Merging DfM and DfD for Competitive Net-Zero Goals

Achieving net-zero objectives while maintaining competitiveness requires a balanced approach that incorporates both DfM and DfD. Simultaneous Engineering offers a strategy to integrate these methodologies, allowing for the concurrent consideration of manufacturing efficiency and circular design principles. For example, (Demartini et al., 2023) argue that circular economy strategies, such as remanufacturing and repair, are essential for managing resource-intensive industries like electric vehicles, where supply chain redesign is necessary to accommodate circular practices. Combining Robust Design, Tolerance Design, and DfD supports SPD by enabling products to be optimized for efficient production while also considering future disassembly and material recovery. By addressing variability during the design phase and planning for circularity, this holistic approach enhances product quality, reduces environmental impact, and strengthens the economic sustainability of manufacturing processes.

2.4 The Need for Updated Competencies in SPD

To effectively implement these integrated approaches, there is a need for updated competencies among designers and engineers. As (Sumter et al., 2021) identify, skills such as Circular Systems Thinking, Design for Recovery, and Circular Business Propositions are crucial for aligning product development with sustainability goals. Training programs must focus on equipping designers with the ability to merge DfM and DfD methodologies while considering circularity from the initial stages of development.

3. Use Case 1: Battery Module Assembly Through DfM

In the assembly of traction batteries for electric vehicles (EVs), establishing reliable electrical connections between battery cells is essential for the overall performance, safety, and lifespan of the battery system. Cells are typically grouped into modules and connected in series and parallel configurations using busbars, which are welded to the terminals to ensure efficient current flow. Maintaining a consistent joint gap between the cells and the busbar is crucial for high-quality bonding and electrical conductivity. However, variations in the manufacturing process can cause deviations in geometrical dimensions, such as the total cell height, leading to inconsistencies in the joint gap (Figure 8, left). These variations must be controlled to meet the maximum permissible joint gap specified by the bonding process.

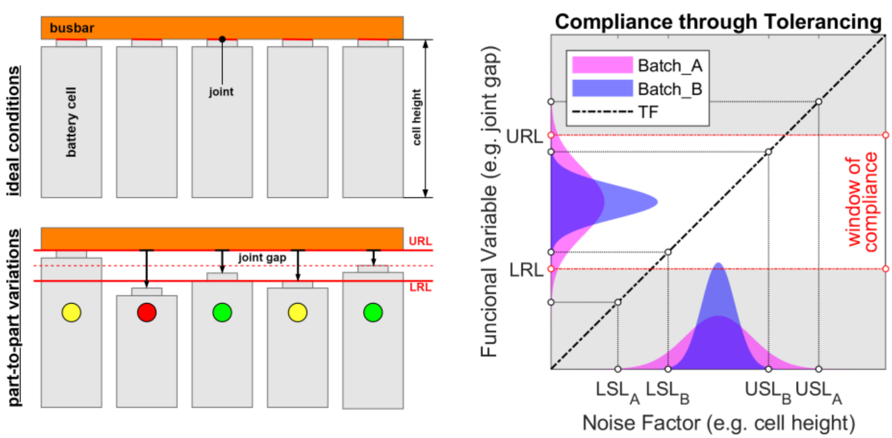

Figure 8: Part-to-part variations in assembly (l), functional compliance via tolerancing (r)

As part of the Design for Manufacturing (DfM) approach, one method for addressing this issue is Tolerance Design. This involves tightening the tolerance specifications for cell height in order to reduce the variability in the joint gap. Figure 8 (right) illustrates that Batch A of battery cells leads to a distribution of joint gap values exceeding the functional requirement limits. By tightening the tolerances

(Batch B), the distribution becomes narrower, allowing the joint gaps to fall within the compliance window. While this approach achieves the desired outcome, it can also result in increased manufacturing costs and higher rejection rates due to the stricter tolerances, potentially impacting competitiveness.

Alternatively, Robust Design principles can be applied to reduce the sensitivity of the joint gap to variations in cell height. Figure 9 (left) shows how introducing a modified transfer function (TF_B) with a smaller slope compared to the original (TF_A) results in a less sensitive response of the joint gap to cell height variations. This reduced sensitivity can be achieved, for example, by adding clamping pressure during the bonding process, allowing the busbar to deform and thus minimize the joint gap. Robust Design, therefore, enhances assembly robustness by addressing variability through product and process design.

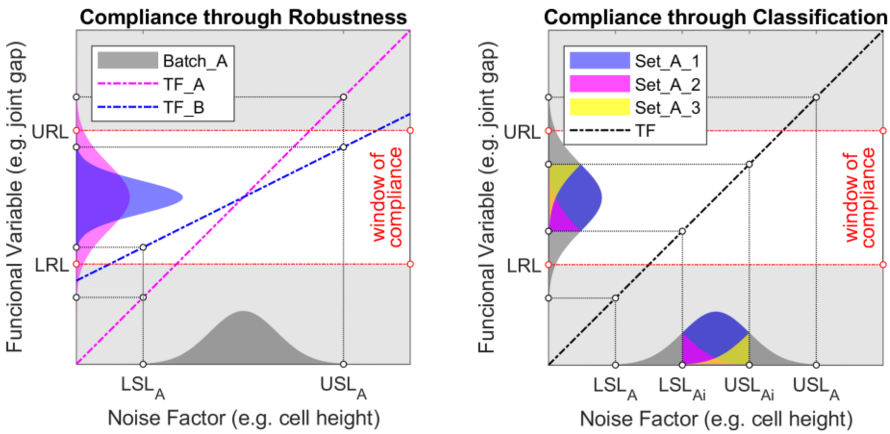

Figure 9: Meeting functional compliance through robustness (l) and classification (r)

Lastly, leveraging the benefits of mass manufacturing, such as mass inspection, can further improve the consistency of battery cells. While cell height distribution is usually estimated from sample measurements, actual dimensions of individual cells remain unknown. Implementing a mass inspection process enables the measurement of all critical parameters, allowing cells to be sorted and grouped into subsets with similar dimensions. Figure 9 (right) shows that this classification approach significantly reduces variability, ensuring that joint gaps remain within the compliance window, thus enhancing assembly quality.

4. Use Case 2: Efficient SOFC Disassembly Through DfD

Solid Oxide Fuel Cells (SOFCs) play a crucial role in achieving net-zero emissions, providing efficient electricity generation from hydrogen and other fuels with low emissions. The cell itself is of particular interest from a circularity standpoint, as it contains a significant amount of critical raw materials (CRMs).

However, the design of contemporary SOFC stacks presents challenges for recovery and reuse, particularly due to high-temperature seals made of glass or ceramics. These seals form strong material-fit bonds upon cooling, making non-destructive disassembly difficult and hindering sustainable lifecycle management.

Figure 10 shows a cross-sectional view of an SOFC stack, which includes two interconnect plates (IC1 and IC2), the Ni-Mesh, and the cell, consisting of the anode, electrolyte, and cathode. The sealing configuration adds complexity, with seals located between the interconnects and between the electrolyte and IC1. The Design Structure Matrix (DSM) on the right visualizes the connections between parts, using colours to represent the bond strength: black for self-connections, green for preloaded connections, orange for the seals, and red for robust material-fit bonds.

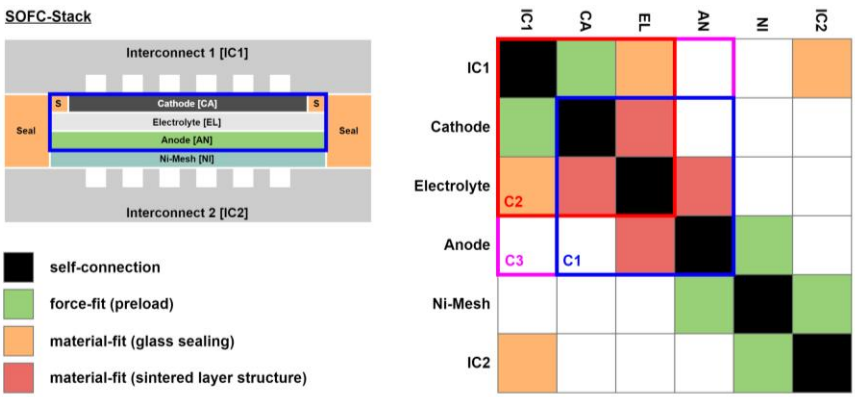

Figure 10: Design Structure Matrix of SOFC-stack showing joint connection characteristics

The DSM analysis helps identify clusters of connected components, which can inform potential disassembly strategies. Both cluster C1 and cluster C2 include strongly bonded components, such as the electrolyte, making separation challenging due to the robust bonds. Alternatively, cluster C3 represents a more practical target for replacement, since the seal between the electrolyte and IC1 does not need to be broken in order to proceed with this approach. This analysis suggests that optimizing component groupings can facilitate circular strategies such as repair, refurbishment, and recycling by reducing the number of challenging connections to be disassembled. Incorporating DfM principles during the early stages of SOFC development can enhance the feasibility of circularity efforts, contributing to more sustainable lifecycle management.

5. Discussion

The use cases demonstrate the importance of early-stage design methodologies, such as Tolerance Design, Robust Design, and Design for Circularity, in achieving sustainable development for net-zero technologies. Integrating these approaches early in the design process improves manufacturing outcomes and circularity. In the battery module assembly example, Tolerance and Robust Design managed joint gap variability, enhancing bonding quality and ensuring consistent electrical connections. These approaches show how addressing variability early can reduce costly adjustments and improve manufacturing efficiency.

For SOFC disassembly, the Design Structure Matrix (DSM) analysis revealed how early design decisions on material selection and bonding strategies impact circularity efforts like repair, refurbishment, and recycling. Identifying clusters of components that can be replaced together reduces disassembly complexity and supports sustainable lifecycle management.

These examples underscore the need to integrate design methodologies with circular economy principles to minimize material waste and reliance on critical raw materials. Challenges remain, such as balancing tighter tolerances with costs or incorporating disassembly costs into design decisions. Further refinement is needed to optimize trade-offs, aligning strategies with industry practices to support net-zero manufacturing.

6. Conclusion and Future Outlook

This paper demonstrates the impact of early-stage design decisions on sustainable product development for net-zero technologies. Integrating Tolerance Design, Robust Design, and Design for Circularity effectively manages variability, improves manufacturing quality, and supports circularity goals. The use cases – battery module assembly and SOFC disassembly – illustrate how aligning design methodologies with circular economy principles enhances reliability and resource efficiency. Future efforts should refine these methods, develop cost models for disassembly, and explore materials that enable easier separation. Incorporating these approaches into engineering education is vital for preparing engineers to address sustainability challenges. Combining manufacturing and circularity strategies can boost competitiveness while advancing long-term sustainability and net-zero objectives.

REFERENCES

[1] Babbitt, C. W., Althaf, S., Rios, F. C., Bilec, M. M., & Graedel, T. E. (2021). The role of design in circular economy solutions for critical materials. *One Earth*, *4*(3), 353–362. https://doi.org/10.1016/j.oneear.2021.02.014

[2] Demartini, M., Ferrari, M., Govindan, K., & Tonelli, F. (2023). The transition to electric vehicles and a net zero economy: A model based on circular economy, stakeholder theory, and system thinking approach. *Journal of Cleaner Production*, *410*, 137031. https://doi.org/10.1016/j.jclepro.2023.137031

[3] Diaz, A., Schöggl, J.-P., Reyes, T., & Baumgartner, R. J. (2021). Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management. *Sustainable Production and Consumption*, *26*, 1031–1045. https://doi.org/10.1016/j.spc.2020.12.044

[4] European Commission. Directorate General for Communication. (2023a). *EU Net-Zero Industry Act: Making the EU the home of clean tech industries*. Publications Office. https://data.europa.eu/doi/10.2775/010539

[5] European Commission. Directorate General for Communication. (2023b). *European Critical Raw Materials Act*. Publications Office. https://data.europa.eu/doi/10.2775/741940

[6] Goetz, S., Schleich, B., & Wartzack, S. (2020). Integration of robust and tolerance design in early stages of the product development process. *Research in Engineering Design*, *31*, 157-173. https://doi.org/10.1007/s00163-019-00328-2

[7] Morse, E., Dantan, J.-Y., Anwer, N., Söderberg, R., Moroni, G., Qureshi, A., Jiang, X., & Mathieu, L. (2018). Tolerancing: Managing uncertainty from conceptual design to final product. *CIRP Annals*, *67*(2), 695–717. https://doi.org/10.1016/j.cirp.2018.05.009

[8] Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain*. PBL Netherlands Environmental Assessment Agency. https://books.google.at/books?id=awuJAQAACAAJ

[9] Schlögl, G., Grollitsch, S., Ellersdorfer, C., Feist, F., Kirschner, C., Ecker, J., & Haas, F. (2024). Sustainable Battery Lifecycle: Non-Destructive Separation of Batteries and Potential Second Life Applications. *Batteries*, *10*(8), 280. https://doi.org/10.3390/batteries10080280

[10] Shahbazi, S., & Jönbrink, A. K. (2020). Design Guidelines to Develop Circular Products: Action Research on Nordic Industry. *Sustainability*, *12*(9), 3679. https://doi.org/10.3390/su12093679

[11] Sumter, D., de Koning, J., Bakker, C., & Balkenende, R. (2021). Key Competencies for Design in a Circular Economy: Exploring Gaps in Design Knowledge and Skills for a Circular Economy. *Sustainability*, *13*(2), 776. https://doi.org/10.3390/su13020776