Sustainable product development framework: Early-stage integration from components to product sustainability – speed pedelec case study

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ABSTRACT

Integrating sustainability considerations into the early stages of the Product Development Process (PDP) is essential for designing environmentally, economically, and socially responsible products. This paper presents a structured and scalable methodology for sustainable product development, applied to the case of a speed-pedelec. The proposed framework introduces intermediate variables to bridge the gap between component-level design variables and product-level indicators. Moreover, a two-stage process for identifying Key Design Variables is also developed. The methodology is designed to integrate seamlessly into existing PDPs through standard evaluation gates and supports iterative refinement as more data becomes available. A case study illustrates the practical application of the framework, with the goal of extending its range. The analysis includes a repairability assessment based on a reduced-order Bill of Materials, validated against full-product calculations. Results not only demonstrate acceptable improvement in range and efficiency, but also a measurable improvement in repairability, confirming the effectiveness of the proposed early-stage methodology. The framework is adaptable to various product domains and supports companies in making informed trade-offs between sustainability, performance, and cost from the earliest stages of design.

1. INTRODUCTION

Reflecting environmental challenges, recent regulations and standards have introduced new sustainability requirements to many sectors in manufacturing (Regulation (EU) 2024/1781) and (International Organization for Standardization [ISO], 2025). Therefore, most of them face the need to estimate and compare relatively new environmental aspects of different product variants early in the Product Development Process (PDP). To enable a new kind of decision-making, conventional PDP must be analyzed, restructured, and extended to address sustainability issues and guiding design decisions (Gagnon et al., 2012) and (Delaney et al., 2022). A Sustainable Product Design (SPD) framework consists of several phases, each representing refined processes, choices, and decisions for developing a new product.

There is a vast number of environmental sustainability indicators that could be considered in SPD (Regulation (EU) 2024/1781), (International Organization for Standardization [ISO], 2025), (de Oliveira et al., 2021), and (Chrispim et al., 2023). While many of the indicators are related to materials constituting products (like environmental footprints and circularity of material flows), there are also indicators reflecting product lifetime extension like durability, and repairability (Regulation (EU) 2024/1781). Currently, there is no standard approach to integrate sustainability indicators into SPD (Kravchenko et al., 2021) and (Parolin et al., 2024). Our assumption is that at the very early stages of SPD a group of experts establishes a sustainability scope and main objectives for a new product.

How early in the SPD process different product design variants become comparable depends largely on the availability and reliability of design data, as well as the validity of any extrapolations derived from it. Several studies aim to shift sustainability decision-making toward earlier PDP phases (Hallstedt et al., 2023), while also addressing the challenges of trade-offs between conflicting objectives (Parolin et al., 2024). This paper takes repairability as a representative example to investigate which data are required to evaluate such a KPI and when this data becomes available during the design process. Using a selected benchmark case, new product design variants are quantitatively assessed across several PDP phases to observe how the availability and granularity of data evolve—and how these influence the development of a reliable repairability score. This process enables tracking of how design deviations impact final product-level KPIs, ultimately supporting the selection of the most suitable design variant.

Although recent regulations increasingly reference repairability, there remains no universal method for quantitatively expressing repairability across all product categories. Most current approaches define product-specific repairability metrics, such as those for washing machines, smartphones, or laptops (Bracquene et al., 2021), (Boix et al., 2024), and (Spiliotopoulos et al., 2019). Common frameworks—such as RSS (Sanfelix et al., 2019), AsMer (Bracquene et al., 2021), EN 45554 (CEN and CENELEC, 2020), and iFixit (Suovanen, 2023)—typically assess a combination of engineering design aspects, support services, and information availability. However, the present study focuses solely on the repairability aspects related to engineering design. Section 2 outlines the reference PDP; Section 3 introduces a generic methodology for integrating sustainability KPIs into PDPs via data tracking from Key Design Variables (KDVs) through intermediate variables to product-level outcomes. Section 4 provides a case-based analysis of repairability evaluation across PDP stages for speed-pedelec variants. And finally, section 5 concludes with discussion and directions for future research.

2. SUSTAINABLE PDP (S-PDP) FRAMEWORK

The generic product design process (Zheng et al., 2014) and (Jiang et al., 2021) is typically structured into four main phases: the Exploration, the Conceptual Design, the Detailed Design, and the Testing and Validation Phase. Each phase builds upon the previous by refining requirements, narrowing down design options, and validating performance to reduce technical and commercial risks. The proposed SPD framework extends this structure by embedding sustainability considerations throughout the entire process. It encourages informed decision-making across disciplines to reduce environmental impact while maintaining economic and functional performance. Integrating sustainability KPIs in the early stages of PDP is essential to ensure that environmental considerations are embedded from the outset. To support this approach, evaluation gates are placed at key transition points—between exploration, conceptual, and detailed design phases—ensuring that sustainability KPIs are systematically reviewed and validated before advancing (Figure 1). Additionally, a robust data flow is also critical, enabling consistent tracking and exchange of environmental data, material properties, and performance metrics.

Figure 1. Gates between the phases of the generic PDP

3. METHODOLOGY

This section introduces a structured methodology to systematically translate component-level design variables (DV) into product-level sustainability KPIs, beginning from the earliest stages of the PDP. Central to this approach is the use of intermediate variables— (Component Performance Metrics (CPMs) and Environmental Variables (ENVs))—which serve as a bridge between design decisions and product KPIs (figure 2). This structure also supports the identification of KDVs (that can be defined as the most impactful design variables) from a broader set of variables, to focus efforts on the most impactful factors.

Figure 2. Component level and product level parameters

3.1 INTERMEDIATE VARIABLES (INV)

Establishing a direct relationship between specific component-level design variables and high-level product KPIs is often highly complex or even impractical. To address this challenge, the proposed methodology introduces intermediate variables (INVs)—quantifiable metrics at the component level categorized into two main groups:

- **Component Performance Metrics (CPMs):** capture the functional and non-environmental performance characteristics of individual components, such as efficiency, power density, and cost.

- **Environmental Variables (ENVs):** reflect environmental impacts, such as carbon footprint, material weight, energy consumption, depth of disassembly, or disassembly time of a component.

A structured scoring methodology is also developed to clarify the criteria when selecting a variable as INVs. (Figure 3).
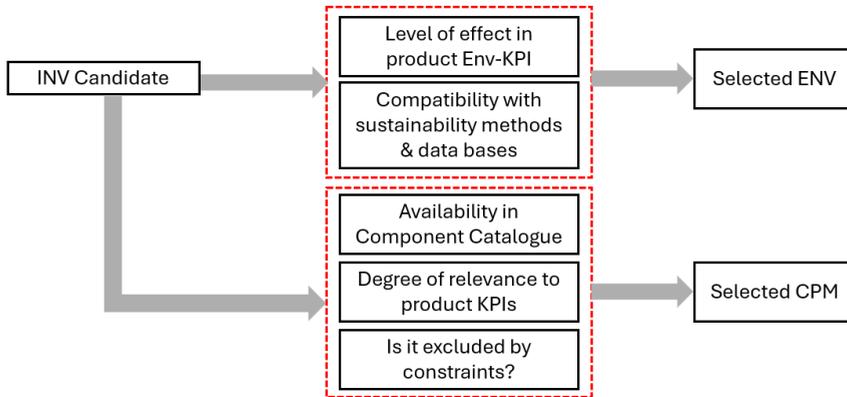

Figure 3. Flowchart of selecting Intermediate variables

3.2 KPI MAPPING PROCEDURE

Once potential INVs are defined, the next step is to establish how they relate to product KPIs. This methodology classifies these relationships into three types based on complexity and data sources:

- **Type 1-Additive (BOM-based):** Simple summation relations, such as component weight contributing to total product weight.

- **Type 2- Functional:** Analytical expressions combining multiple CPMs/ENVs, for example, overall product efficiency may depend on the efficiencies of several interacting components.

- **Type 3- Data-driven:** When additive or formulaic relations are not feasible, empirical models are used. This approach relies on data from simulations, tests, literature, or databases to create multi-dimensional lookup tables that relate IVs to KPIs.

3.3 FROM DESIGN VARIABLES TO INVS

Once the product-level KPIs are reliably linked to a set of intermediate variables, the next step is to establish how these INVs are influenced by

component-level design variables. Proposed methodology categorizes them into two groups based on the quantifiability of the design variables:

- **Design Effect Matrix (DEM):** For quantifiable DVs, the DEM serves as a structured, multi-dimensional lookup table that maps their influence—both direct and cross-effects—on specific IVs.

- **Type Selection Matrix (TSM):** For non-quantifiable or categorical DVs (e.g., motor type, battery cell chemistry), the TSM functions similarly to the DEM. It provides a rule-based or data-driven framework to estimate the influence of design choices that cannot be expressed through numeric scales.

3.4 KEY DESIGN VARIABLES IDENTIFICATION

In the development of complex products, the number of potential DVs can be vast—often in the thousands therefore, identifying a focused set of KDVs is essential. The KDV identification process consists of two stages (Figure 4):

Stage 1: Design-Level Evaluation: Each DV is scored based on four critical aspects:

- *Feasibility in Manufacturing*
- *Multi-KPI Effect*
- *Definability as the product KDVs*
- *Dependency Level to other KDVs*

Stage 2: KPI-Relevance Evaluation: DVs that pass the first stage are further assessed based on their relationship to INVs or to KPIs.

- *Breadth of Impact on INVs*: DVs with broader and more significant influence on multiple INVs (CPMs or ENVs), and thus on product KPIs, are prioritized.

- *Sensitivity*: DVs that exhibit high sensitivity—where small changes lead to significant effects on INVs or KPIs—are considered strong candidates for KDVs.
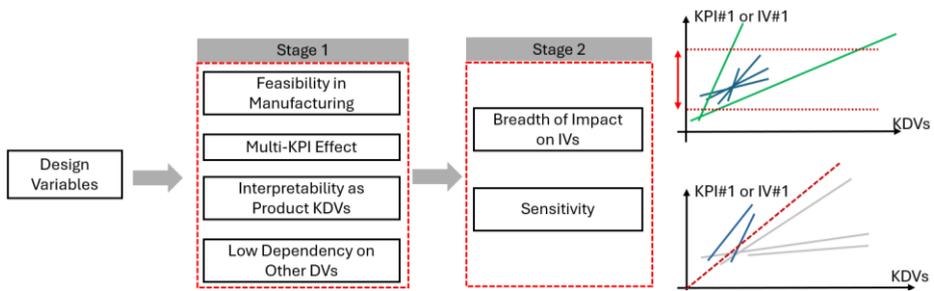
Figure 4. Flowchart of scoring of DVs to clarify KDVs. Stage 1, represents the first scoring stage. Stage 2 performs sensitivity analysis and impact analysis of each DV on the product KPIs.

3.5 INTERACTION OF PROPOSED METHODOLOGY WITH CURRENT PDP

Most companies operate with an established PDP that has evolved and proven effective over time. Therefore, it is essential to clarify how the proposed methodology integrates with the existing PDP without disrupting its core structure. To illustrate this interaction, the PDP is analysed in terms of its inputs and outputs, and its connection to the proposed methodology is visualized in Figure 5. The methodology interfaces seamlessly with the existing PDP, operating in parallel rather than requiring structural modifications. A key component is the iteration decision block, which evaluates whether a given combination of KDVs and the resulting product-level KPIs satisfies the design requirements. If not, the process allows for iterative refinement of KDVs.
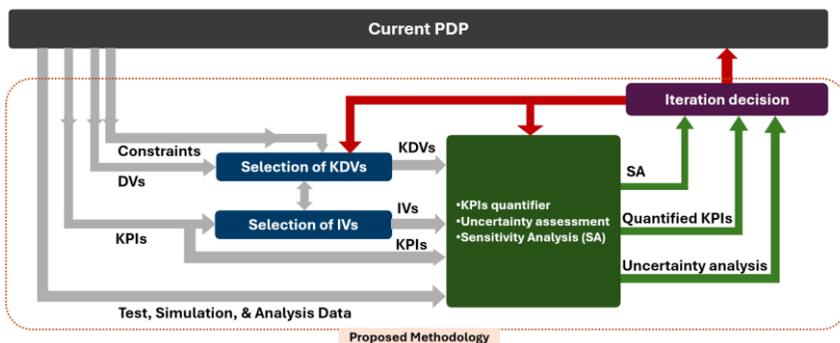

Figure 5. Interaction of the proposed methodology with the current PDP

3.6 DATA AVAILABILITY AND INTEGRATION GATES

Another key consideration is the identification of appropriate integration points—referred to as gates (Figure 1)—within the existing PDP. At each gate, the methodology can be activated to assess and quantify results, using available data at that stage. These results can then be evaluated not only through the standard PDP trade-off approach but also compared with outcomes from previous gates. This iterative comparison enables tracking of performance trends and, importantly, allows for the evaluation of uncertainty and sensitivity as the PDP progresses.

4. SPEED PEDELEC CASE STUDY & REPAIRABILITY AS-SESSMENT

4.1 PRODUCT DESIGN SCENARIO

A Speed Pedelec has been selected as the case study for applying the proposed methodology. Rather than developing an entirely new design, the scenario begins with an existing product. Due to the limited availability of detailed design data for this product, a series of ad-hoc methodologies was employed to generate diverse yet coherent datasets, with careful attention to maintaining realism and consistency. The primary objective is to improve a KPI—the bike's range—from 40.7 km to over 95 km. In addition to this KPI, a subset of KDVs has been identified for potential modification, based on the methodology outlined in the previous section. These KDVs include motor speed, motor type, motor location, number of batteries, and transmission type. Furthermore, the repairability of the redesigned product will be evaluated as a sustainability-related KPI to demonstrate the effectiveness of the proposed approach.

4.2 REPAIRABILITY ASSESSMENT OVERVIEW

Several reference methods assess repairability based on common aspects: *priority part selection*, *Depth of Disassembly* (*DoD*), *Disassembly Time* (*DT*), *Tools Score* (*TS*), and *Fastener Score* (*FS*) (Wandji et al., 2023). Rather than calculating a single weighted score, these metrics are used as INVs within the PDP.

The priority parts are selected based on *functional importance* and the *failure frequency* of the components, not economic or environmental impact, they are motor, battery, and transmission.

The next metric to calculate is the DoD, which is defined as the number of steps to remove a part without damage. The level of detail depends on the PDP stage and available data. Early phases may only allow part removal counts; detailed design will include tool changes as the steps too.

The other metric (DT) is defined as the sum of four key components: fastener time, tool change time, handling time, and access time.

- *Fastener time* accounts for the number of joints and their associated disassembly durations, which may depend on joint type and length.

- *Tool change time* reflects the additional time required to switch between different tools during disassembly, including specific tools like torque wrenches.

- *Handling time* estimates the time needed to safely handle and remove the component, based on its size, shape, and complexity.

- *Access time* represents the cumulative time needed to remove other components that obstruct access to the target part. It aggregates the fastener, tool change, and handling times of those preceding components.

Tool Score (TS) is the other aspect in this methodology, and it takes the effect of tool complexity, availability, and changing penalties into account. Fastener Score (FS) is the final metric that considers the fastener reusability, their potential to cause damage, and the number of the fasteners.

After calculating all these previous metrics, they are normalized between 0-10. Thereafter, for each component in priority list, the ith component repairability score can be calculated, based on the below equation:

$$RS_i = w_1 \times DoD_i + w_2 \times DT_i + w_3 \times FS_i + w_4 \times TS_i$$

$$(1)$$

Then using the weight factor for each component from the priority list the final product repairability score can be evaluated easily.

4.3 REPAIRABILITY RESULTS

Table 1 presents the calculated repairability scores for both individual priority components and the overall product, based on a Reduced-Order BOM. In this context, the reduced-order BOM refers to a subset of four critical components—selected from a total of approximately 20 in the S-Pedelec—for analysis under the range extension scenario. The overall repairability score of the product is, therefore, estimated by focusing solely on these four components as the priority list.

As the PDP advances from the Exploration (Exp.) to the Detailed Design phase (Det.), uncertainty in the design is reduced and the reliability of the data improves. The variation between the Reduced-Order BOM results in the Detailed Design phase with exploration and Conceptual phases (Con.) are 30% and 0.098% respectively. This trend highlights the increasing accuracy of repairability predictions as the PDP advances and as a result the data availability and reliability improve. To further assess the accuracy of the Reduced-Order approach, a full repairability analysis was conducted using the complete BOM, with results presented in the final row of Table 1. The deviation between the Reduced-Order and Complete BOM results across all PDP phases ranges between 3.8% and 22%, confirming that the proposed methodology can estimate repairability with acceptable precision even in the early design stages.

Table 1. Repairability score for product and priority list components in different PDP stages

Target view for Repairability Score	Repairability Score Value						
	Previous product	Mid motor Configuration			Hub motor Configuration		
		Exp.	Con.	Det.	Exp.	Con.	Det.
Motor	7,68	7,41	7,33	7,32	8,00	8,01	8,01
Battery down	9,52	9,45	9,52	9,52	9,44	9,52	9,52
Battery Up	-	3,00	9,90	9,90	3,00	9,89	9,89
Transmission	8,56	5,24	8,56	8,54	5,40	8,57	8,54
Product Reduced BOM	8,58	6,13	8,79	8,78	6,31	8,93	8,93
Product Complete	8,42	7,94	8,47	8,46	7,98	8,50	8,50

To test the methodology under architectural variation, a second analysis was performed using a Hub Motor configuration. The results are shown in three

right hand side columns of Table 1 and are consistent with the previous findings: deviation from Detailed Design results is highest in the Exploration phase and decreases as the design matures. The deviations across all PDP phases for this configuration fall within 5% to 21%. Additionally, a comparison between the Hub and Mid motor configurations reveals that the Hub Motor setup offers a 1.6% higher repairability score, indicating a marginal advantage in this KPI. Finally, a comparison of the overall repairability scores of the new product (in both configurations) against the original product confirms an overall improvement in repairability—despite the inclusion of a second battery in the design.

Table 2. Final Product KPIs and KDVs Compared to Original Configuration

Previous Product			New Product		
KPI	**Unit**	**Value**	**KPI**	**Unit**	**Value**
Range	km	40.72	Range	km	107
Efficiency	%	62.9	Efficiency	%	85
Repairability		8.42	Repairability		8.50
KDV	**Unit**	**Value**	**KDV**	**Unit**	**Value**
Rated speed	kph	20	Rated speed	kph	30
Motor Type		SRM	Motor Type		PMSM
Motor Location		Mid	Motor Location		Hub
# of Batteries		1	# of Batteries		2
Battery #1 Capacity	Wh	500	Battery #1 Capacity	Wh	400
Battery #2 Capacity		-	Battery #2 Capacity	Wh	500
Transmission type		Chain	Transmission type		Belt

This suggests that the revised architecture not only enhances performance KPIs (e.g., range and efficiency) but also preserves or improves serviceability. Table 2 summarizes the KPIs of the final selected configuration compared to the original model, highlighting the tangible improvements achieved through the proposed design methodology. The range, which was the primary objective of the redesign, increased by approximately 162%, from 40.72 km to 107 km. In addition, the new configuration led to a 35% improvement in efficiency and a 1% increase in the repairability score, demonstrating that performance and serviceability were enhanced simultaneously.

5. CONCLUSION

This paper presented a structured methodology for integrating sustainability-focused KPIs into the early stages of the PDP, with a particular emphasis on the design of a speed pedelec. The proposed Sustainable PDP framework enables a systematic translation of component-level design variables into product-level sustainability outcomes using intermediate variables—specifically Component Performance Metrics and Environmental Variables.

A two-stage process for identifying KDVs was introduced, enabling design teams to focus on the most influential parameters across various KPIs. Additionally, the use of DEM and TSM matrices allowed for a traceable mapping of design decisions to sustainability and performance metrics. Integration points with existing PDP structures were clearly defined, and the methodology was shown to function effectively within standard gate-based development frameworks.

The case study on a speed pedelec demonstrated the practical application of the methodology, focusing on extending the vehicle's range while also evaluating improvements in repairability and efficiency. The results validated the accuracy of the reduced-order BOM approach and confirmed the convergence of early-phase estimates toward final design outcomes. Notably, a 162% increase in range, a 35% improvement in efficiency, and a measurable increase in repairability were achieved, demonstrating the strength of this early-stage sustainability-driven design process.

Future research can build on this methodology by extending it to full lifecycle assessments, incorporating end-of-life factors such as recyclability and disassembly. Further opportunities include integrating multi-objective optimization tools for automated trade-off analysis, adapting the framework to other product domains like electric vehicles or industrial systems, and leveraging digital twins and AI-based tools for real-time KPI estimation and design feedback. Overall, this research offers a scalable and practical foundation for embedding sustainability into early-stage product development, guiding companies toward more informed and responsible design decisions.

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REFERENCES

Bracquene, E., Peeters, J., Alfieri, F., Sanfelix, J., Duflou, J., Dewulf, W., & Cordella, M. (2021) Analysis of evaluation systems for product repairability: A case study for washing machines. Journal Of Cleaner Production, 281. https://doi.org/10.1016/j.jclepro.2020.125122

Boix Rodríguez, N., Chiastra, L., Peeters, J. R., & Favi, C. (2024) Analysis of repairability index to improve disassemblability and serviceability in cooker hoods. Procedia CIRP, 122, 801 – 806. https://doi.org/10.1016/j.procir.2024.01.112

Chrispim, M. C., Mattsson, M., Ulvenblad, P. (2023) The underrepresented key elements of Circular Economy: A critical review of assessment tools and a guide for action. Sustainable production and consumption, 35(1), 539–558. https://doi.org/10.1016/j.spc.2022.11.019

Delaney, E., Liu, W., Zhu, Z., Xu, Y., & Dai, J. S. (2022). The investigation of environmental sustainability within product design: A critical review. Design Science, 8(1), e15. https://doi.org/10.1017/dsj.2022.11

de Oliveira, C. T., Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. Sustainable Production and Consumption, 26(4), 455–468. https://doi.org/10.1016/j.spc.2020.11.024

CEN (European Committee for Standardization) and CENELEC (European Committee for Electrotechnical Standardization). (2020). General methods for the assessment of the ability to repair, reuse and upgrade energy-related products (EN Standard No. 45554:2020). https://standards.iteh.ai/catalog/standards/clc/ed9b48c0-a4a9-421a-a14f-4ff341199918/en-45554-2020?srsltid=Afm-BOooTGY1D4fQw2Tsg41LpLiVdW3dGaCa8W4PTvKxyAbVv7dXq3cX2

European Parliament and Council. (2024). Regulation (EU) 2024/1781 on ecodesign requirements for sustainable products. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1781

Gagnon, B., Leduc, R., & Savard, L. (2012). From a conventional to a sustainable engineering design process: Different shades of sustainability. Journal of Engineering Design, 23(1), 49–74. https://doi.org/10.1080/09544828.2010.516246

Hallstedt, S. I., Villamil, C., Lövdahl, J., & Nylander, J. W. (2023). Sustainability Fingerprint - guiding companies in anticipating the sustainability direction in early design. Sustainable production and consumption, 37(5), 424–442. https://doi.org/10.1016/j.spc.2023.03.015

International Organization for Standardization. (2025). Circular economy — Product circularity data sheet (ISO Standard No. 59040:2025). https://www.iso.org/standard/82339.html

Jiang, P., Dieckmann, E., Han, J., & Childs, P. R. N. (2021). A bibliometric review of sustainable product design. Energies, 14(21), 6867. https://doi.org/10.3390/en14216867

Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2021). A Trade-Off Navigation Framework as a Decision Support for Conflicting Sustainability Indicators within Circular Economy Implementation in the Manufacturing Industry. Sustainability, 13 (1), Article 314. https://doi.org/10.3390/su13010314

Parolin, G., McAloone, T. C., & Pigosso, D. C. A. (2024). What's the catch? Trade-off challenges in early design for sustainability. Proceedings of the Design Society, 4, 1399–1408. https://doi.org/10.1017/pds.2024.142

Sanfelix, J., Cordella, M., & Alfieri, F. (2019). Analysis and development of a scoring system for repair and upgrade of products. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/725068

Spiliotopoulos , C., Duflou, J., Alfieri, F., La Placa, M. G., Bracquene, E., Laps, E., Van Moeseke, T., Dangal, S., Bolanos A. J., Flipsen, B., Faludi, J., & Balkenende, R. (2019). Product reparability scoring system: specific application to smartphones and slate tablets. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/340944

Suovanen, J. (2023). How is the iFixit Repairability Score Calculated? iFixit. https://www.ifixit.com/News/75533/how-ifixit-scores-repairability

Wandji, C., Rejeb, H. B., Riel, A., Zwolinski, P., & Zuanna, C. D. (2023). Leveraging circularity through repair standards: A comparison of methods for assessing product reparability for extended use on mechanical products. Procedia CIRP, 120, 273–278. https://doi.org/10.1016/j.procir.2023.08.049

Zheng, C., Bricogne, M., Le Duigou, J., & Eynard, B. (2014). Mechatronic design process: A survey of product data model. Procedia CIRP, 21, 282–287. https://doi.org/10.1016/j.procir.2014.03.176