Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 140 (2026) 449–454

www.elsevier.com/locate/procedia

33rd CIRP Conference on Life Cycle Engineering (LCE 2026)

Engineering design for disassembly: test of a time-based methodology and the LeanDfD software tool

Emeka Igwe[a], Claudio Favi[b*], Marco Marconi[c], Marco Mandolini[d], Anoop Desai[a]

[a]*Georgia Southern University, Statesboro, 30458 Georgia, USA*
[b]*Università degli Studi di Parma, Parco Area delle Scienze 181/A, 43124 Parma, Italy*
[c]*Università degli Studi della Tuscia, Largo dell'Università, 01100 Viterbo, Italy*
[d]*Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy*

* Corresponding author. Tel.: +39-0521 90 2911. *E-mail: claudio.favi@unipr.it*

Abstract

This study evaluates the performance of a time-based methodology and the associated software tool (i.e., LeanDfD) developed for assessing product disassemblability. LeanDfD enables design engineers to analyze disassembly sequences and times, and to derive targeted redesign recommendations to enhance disassembly efficiency. The methodology is applied to two case studies: a low-complexity electric blender and a high-complexity soda vending machine. Tool-generated disassembly time estimates are validated against experimental measurements, and the impact of implementing LeanDfD's redesign suggestions is assessed. Results indicate that LeanDfD predicts disassembly times for the electric blender with an average error of 8%. Furthermore, applying LeanDfD-based redesign recommendations to the soda vending machine results in a roughly 20% reduction in disassembly time.

Keywords: Engineering design; demanufacturing; design for disassembly; DfD; digital twin.

1. Introduction and literature review

As industries rapidly adapt to evolving regulatory frameworks and increasingly stringent sustainability targets, integrating systematic Design for Disassembly (DfD) principles into the early stages of product development has become an enabler. DfD represents a structured, time-oriented approach in which engineers and designers strategically incorporate disassembly considerations into product design, accounting for the long-term costs associated with maintenance, upgrades, and end-of-life recovery [1]. Beyond its conventional definition as a concept aimed at simplifying product disassembly, DfD serves as an engineering methodology for identifying and embedding design specifications that minimize structural complexity. This ensures that products can be efficiently dismantled into their constituent components or materials, thereby facilitating maintenance operations, enhancing recyclability, and supporting circular economy objectives [2][3]. In recovery processes like remanufacturing, disassembly is essential as a prerequisite for a successful recovery of valuable resources [4][5]. There are multiple drivers for adopting DfD techniques. Impending legislation (e.g., WEEE and RoHS) is one reason that has pressurized manufacturers into adopting sustainable product design principles, but designing for disassembly is not just about meeting legal requirements [6]. Several methods have been developed in response to growing interest in sustainability to consider the broader environmental impact of industrial processes and products [7]. One sustainable strategy that addresses the declining state of the environment and public demand for a clean and healthy environment is DfD [8].

10.1016/j.procir.2026.05.076

From the 1980s, numerous research and development initiatives significantly advanced the field of DfD. This period marked the peak in scholarly publications on DfD-related topics, contributing to a redefinition of its role and influencing the integration of disassembly-oriented strategies in contemporary product manufacturing practices [9]. In more recent years, DfD has increasingly been recognized as a multidisciplinary concept that links product design methodologies with waste management and environmental sustainability principles, applicable to both industrial product development and building design [10]. One of the prototype tools developed to support DfD implementation was the End-of-Life Design Advisor (ELDA) software. ELDA was designed to assist product developers in defining appropriate end-of-life strategies by aligning them with the technical characteristics and structural attributes of the product [11]. Pnueli et al. [12] proposed another DfD-oriented approach, aiming to define an algorithmic method that integrates recycling as a core end-of-life strategy. This tool systematically analyzes product designs within a defined framework to identify structural weaknesses and generate targeted recommendations to improve disassembly and material recovery.

Building on recent research by Favi et al. [13] a tool named LeanDfD was developed to address key factors influencing disassembly efficiency and end-of-life product design. While many software tools in the literature aim to identify the disassembly sequence that minimizes the number of disassembly tasks or the disassembly depth, LeanDfD computes the sequence that guarantees the shortest time. The methodology embedded in LeanDfD emphasizes: (i) reducing the number of parts and optimizing material usage during assembly, (ii) minimizing both the number and duration of disassembly task, and (iii) facilitating the straightforward separation of components. The LeanDfD tool was developed to support design engineers in developing strategies for ease-of-disassembly evaluation. [13–18].

This research aims to evaluate a time-based methodology [19] for disassemblability assessment using the LeanDfD software tool. The tool is applied to two products, an electric blender and a soda vending machine, that differ in the complexity of their Bills of Materials. By following the disassembly sequences and times estimated by LeanDfD, a comparison was made with experimental time measurements to assess the tool's reliability in estimating disassembly performance. Afterwards, the study investigates the potential benefits of implementing the redesign suggestions generated by LeanDfD, to optimize products for faster and more efficient disassembly. While the scope of this work does not include the development of new fastening technologies or manufacturing processes, it focuses on improving existing product designs through informed redesigns and on enhancing disassembly efficiency through time-oriented evaluation.

2. Time-based disassembly methodology and the LeanDfD software tool

This section describes the time-based DfD approach and the related LeanDfD tool employed in this study.

2.1. Design for disassembly approach

Assessing the disassembly time and cost of a selected target component is done via a four-step methodology called Disassembly Analysis [19], which is presented as follows.

1. *Selecting target components*. Target components are defined as parts that must be disassembled non-destructively during the product's useful life due to one or more of the following factors: (i) the need for regular maintenance or servicing, (ii) the presence of hazardous materials, (iii) high residual economic value, and (iv) the use of materials that are incompatible with others in the assembly.
2. *Defining precedencies*. The general rule used to define the presidencies states that "if a generic component "A" must be disassembled after another component "B", then generic component "A" must give precedence to another component "B". The product's subassemblies and components are separated into various disassembly levels following this rule. A more detailed breakdown of the technique and guidelines to follow is described in previous research [19].
3. *Defining liaisons and properties*. It defines the connection between two components that a specific disassembly operation can remove. Liaisons have been subdivided into two hierarchical levels: classes and types. The standard disassembly time depends on the reference liaison, which is disassembled with a specific tool and in a standard state (i.e., not rusted or worn). The data used for defining liaisons and properties is obtained from the Liaison DB repository. It is a tested and trusted knowledge repository created from information retrieved from a wide array of analyses performed for different product families (e.g., electric and electronic equipment, vehicle, and industrial machinery) [16].
4. *Calculating disassembly times and costs*. The disassembly time for each operation (related to a liaison removal process) is calculated by multiplying the standard disassembly time by various corrective factors based on the specified liaison properties. The disassembly time for each feasible sequence can be calculated by adding the contributions of all disassembly operations. The cost can be successively derived by multiplying the time by the unitary labor and equipment costs. The estimated values enable the determination of which disassembly processes and product criticalities are the most costly or time-consuming. The optimal disassembly sequence is determined using a mathematical optimization approach that selects feasible sequences from the numerous possible alternatives, as extensively described in previous research [13].

2.2. LeanDfD tool

The LeanDfD tool used in this work is a software tool that applies an estimation method (with virtual representations of the actual product) to assist designers in easy disassembly evaluation and in modifying product features to reduce disassembly operations, time, and cost. LeanDfD's design approach aims to increase the disassembly of industrial products and to guide designers to realize the EoL closed-loop lifecycle [14]. The tool can estimate disassembly times and propose optimized disassembly sequences that minimize the overall time required to remove components. LeanDfD incorporates an embedded 3D CAD model environment that enables designers to critically analyze and evaluate a product's disassembly characteristics, facilitating a more accurate assessment of its ease of disassembly during the design phase. The product's virtual model (3D CAD model) serves as the initial input data. This model needs to be imported via the Import Interface (first module) and navigated using the 3D Viewer (second module). All the information required to complete the assessments is contained in these virtual representations when combined (e.g., connections between components, product structure, and materials). Computing the feasible disassembly sequences allows the Product Disassemblability Module to determine the optimal disassembly sequence. The effective disassembly time and cost are calculated by using data stored in the Liaison DB. After the evaluation stage, the results are exported and displayed using the Export Interface. The design framework underpinning LeanDfD enables engineers to assess disassembly time relative to a specific target (T*) and to suggest redesign strategies. T* depends on a variety of factors, including: the product/component's characteristics being analyzed (e.g., economic value), the designer's strategy (e.g., cost-benefit analyses for various EoL scenarios, normative compliance). LeanDfD incorporates disassemblability analyses and specific re-design recommendations using intricate mathematical models. The parameters used to define and understand these mathematical models include: (i) the number of items to remove to reach the target component, (ii) the derivative of cumulative disassembly time (t) concerning a single disassembly operation (x), and (iii) the target time for a single disassembly operation.

3. Design for Disassembly test

This section presents the two case studies analyzed using LeanDfD. The first (an electric blender) aims to evaluate LeanDfD reliability in finding the optimal disassembly sequence and in assessing disassembly time for selected target components. The second (a soda vending machine) aims to evaluate the reduction in disassembly time given by adopting the redesign suggestions proposed by LeanDfD.

3.1. Case Study 1 (electric blender): LeanDfD reliability on disassembly time

A simple household blender is analyzed as a case study using LeanDfD (Fig. 1). First, the target 3D CAD model of the electric blender is imported into LeanDfD, which acts as a digital twin of the disassembly process for selected target components. Target components are chosen from the Bill of Materials in compliance with legislative policies, maintenance requirements, remanufacturing, and material recovery opportunities (Table 1). The virtual disassembly of the target components is simulated based on predefined precedencies, component relationships, and the types and numbers of liaisons

Fig. 1. The electric blender (cross-section view on the right) virtual model.

Table 1. Blender Bill of Materials and target components to disassemble.

Bill of Materials	Target component?	Purpose for disassembly			
		Legislation Policies	Maintenance	Remanufacturing	Material Recovery
Blades x 2 (B)	X		X	X	X
Top cover (TC)					
Lid (L)					
Blades holder (D)	X			X	
Motor (M)	X		X	X	X
Housing (H)					
Regulator (R)	X	X	X		
Power supply cable (W)	X		X		
Jar (J)					
Base cover (BC)					

The precedence relationships among components are defined to determine the order in which parts should be disassembled (Fig. 2).

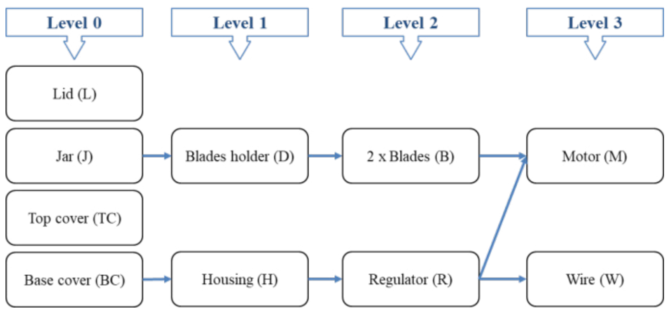

Fig. 2. Disassembly level and precedence flow graph.

Components/Subassemblies on level 0 (the lid, jar, top cover, and base cover) were disassembled first. Components on level 1 can only be disassembled after the components on level 0 have been removed. The arrow indicates the precedence of components. At level 3, it is observed that the electric motor has two precedence connections. This means the electric motor can only be disassembled after the blade and regulator have been removed. The next step in the disassembly analysis of the blender involves defining the liaisons between components, which represent the interconnections that govern their precedence in the disassembly sequence. During this phase, the product's current condition is assessed, including corrosion, dust accumulation, and the extent of any deformation. The appropriate disassembly tools are identified, and the class and type of each liaison are specified to support accurate and efficient disassembly planning. The final step of the disassembly analysis involves calculating feasible disassembly sequences that yield the desired target components. Analyzing the disassembly level and precedence flow graph (Fig. 2), it is observed that the disassembly sequence will start with either the lid (L), jar (J), top cover (TC), or base cover (BC), as they all belong to level 0. For each level of disassembly and component removal, the level matrix is updated through this continuous iteration. This process enables the analysis of the desired target components. The operation with the lowest disassembly time is the best disassembly sequence.

3.2. Case study 2 (vending machine): LeanDfD benefits on disassembly time

The second case study analyzed with the LeanDfD methodology and tool is a vending machine (Fig. 3).

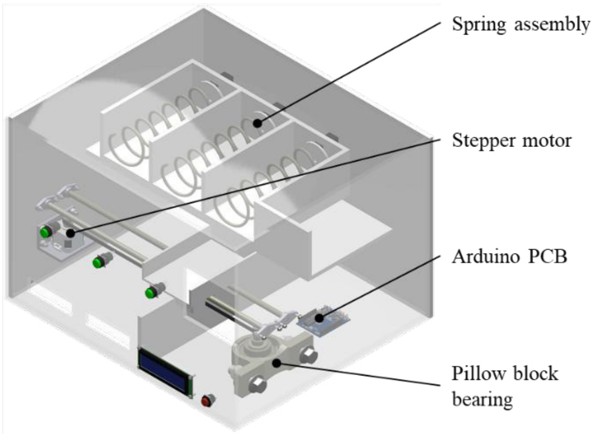

Fig. 3. The soda vending machine virtual model.

The analyzed target components and the motivation behind their disassembly choices are described in Table 2.

Table 2. Vending machine target components to disassemble.

Bill of Materials	Purpose for disassembly: Legislation Policies	Maintenance	Remanufacturing	Material Recovery
Stepper motor		X	X	
Arduino PCB	X			X
Pillow block bearing		X	X	
Spring assembly		X	X	X

The disassembly analysis followed the same methodology used for the electric blender. The tool provides information on a set of criticalities of the disassembly process (e.g., time-consuming operations and the number of components that must be removed before reaching the target component). The spring assembly and the vend motor take the longest to disassemble, with total times of 311 seconds and 246 seconds, respectively. This is undesirable for maintenance purposes, as it will take longer to reach the spring assembly, resulting in more downtime for the vending machine. The tool has also identified other criticalities that indicate the need for a redesign, as follows.

- *Items to remove to reach the electric motor* ≥ Nr
- $\frac{\Delta t}{\Delta x} = \frac{t(Shaft\ panel) - t(Pillow\ block\ bearing)}{1} \geq T^*$
- $\frac{\Delta t}{\Delta x} = \frac{t(Extreme\ back\ panel) - t(Extreme\ right\ panel\ )}{1} \geq T^*$
- $\frac{\Delta t}{\Delta x} = \frac{t(Extreme\ back\ panel) - t(Extreme\ top\ panel)}{1} \geq T^*$
- $\frac{\Delta t}{\Delta x} = \frac{t(Extreme\ top\ panel) - t(extreme\ bottom\ panel)}{1} \geq T^*$

Four panels account for over 85% of the components that increase the disassembly depth of all the target components. T^* was set to 20s and Nr to 10. These parameters were selected to balance measurement accuracy and practical feasibility. For example, a T^* value of 20 s ensures that individual disassembly operations are long enough to be reliably timed while remaining representative of typical manual handling durations. To reduce the disassembly time to reach target components, redesign actions have been implemented as follows.

- The initial design consisted of individual panel members assembled using 72 screws. In the new design, by reworking the extreme back panel, shaft panel, and right panel into a single member, 24 screw liaisons were removed. The redesign also improved space utilization efficiency within the vending machine from 52% to 72%, thereby expanding the compact housing and improving the internal space and access gaps considerably.
- There were two redesign suggestions for the Top panel. The Top panel was redesigned from 6 screws per side to 4 rivets per edge, thereby improving safety by eliminating multiple pinch points created by screw points on the overlapping panels. For ease of maintenance, an access hatch was designed into the top panel, providing direct access to the spring assembly. A hinge liaison was utilized to facilitate opening the new access hatch on the top panel.
- To improve aesthetics, ease of restocking the vending machine, and ease of disassembly, the front panel was redesigned from a fixed liaison with six screws to a temporary liaison that uses two hinges and a snap-fit.
- To improve ease of electronic maintenance, the Arduino PBC was redesigned by reducing the 4 screws to 2 screws and two snap fits. Arduino's position was also moved from the back panel to the front panel to ease reach and improve cost efficiency by reducing the length of conductors between the electrical and electronic components.

4. Results and discussion

4.1. Case Study 1: the electric blender

The disassembly time of the electric blender assessed by LeanDfD data is compared with experimental data measured from carrying out a non-destructive disassembly of a real blender (in use for about two years), shown in Fig. 4. The experimental non-destructive disassembly was carried out twice using basic hand tools like nose pliers, cutters, screwdrivers, and Allen keys, and a stopwatch for recording time. The experiments were carried out by a mid-level male technician (with 1 year of experience) and a male expert technician (with about 3 years of experience). Both disassembly activities replicated the best disassembly sequence from the LeanDfD tool's calculation and recommendation. However, the experiment with the shortest disassembly time was preferred and recorded in this study.

Fig. 4. Experimental disassembly of an electric blender.

Table 3 records the best disassembly times for the target components in the electric blender, determined by both the LeanDfD tool and experimental disassembly.

Table 3. Comparison of calculated and measured disassembly times for the electric blender.

Target Components	Calculated disassembly time [s]	Average experimental disassembly time [s]	Reliability [%]
Blade holder (D)	13.0	14.0	-7.1
Blade (B)	20.9	23.0	-9.1
Regulator (R)	28.7	30.0	-4.3
Power supply cable (W)	29.5	30.0	-1.7
Motor (M)	38.7	45.0	-14.0
TOTAL	130.8	142.0	-7.9

The experimental disassembly times are systematically higher than the calculated times as reported in Table 3 (mean deviation: -7.9%, standard deviation: 4.7%). The error for the blade holder (7.1%) falls within a reasonable prediction error range, confirming that the estimation method is still reliable overall for simple mechanical fasteners. The control regulator (-4.3%) has a low deviation. It is assembled using a standardized fastening method (e.g., screws or snap-fit connections), which LeanDfD can accurately estimate. The power supply cable has the lowest deviation (-1.7%).

The highest deviation (-14%) is for the electric motor, primarily due to challenges with its mounting, its complexity, and the need for additional securing. The electric motor is connected to wiring and structurally assembled with components that may have limited accessibility, hidden access issues, handling precautions, and wear potential. These factors, beyond the current scope of LeanDfD modelling capabilities, increase disassembly effort during disassembly experiments. The LeanDfD tool does not fully account for factors such as component nesting, ergonomic access, wiring complexity, product re-orientation, or the need for specialized disassembly tools.

To improve the existing blender disassembly process, redesign can include incorporating a quick-release mechanism for the blades, as they are components that need to be removed more frequently due to their frequent use. Modular mountings are recommended for critical components, such as electric motors, and snap-fit brackets are preferred over multiple screws. For electrical connections and components, plug-in connectors are preferred instead of soldering. Color-coded and labeled wiring can also facilitate easy access to wiring. In general, the use of standardized fasteners can also reduce disassembly time.

4.2. Case Study 2: the vending machine

The redesign process suggested by the LeanDfD tool resulted in a significant reduction (-20%) in disassembly time for all target components.

Table 4. Comparison between the Original and the New designs of the vending machine.

Target Component	Version	Disassembly Time [s]	Liaisons reduction [No.]	Disassembly time reduction [%]
Arduino PCB	Original New	194.5 154.0	16	-21
Pillow block bearing	Original New	201.7 168.0	24	-17
Spring assembly	Original New	310.5 241.8	28	-22
Stepper motor	Original New	245.8 195.1	5	-21
TOTAL	Original New	952.5 758.9	73	-20

A decrease in disassembly time of at least 17% is recorded across all target components, totaling 17 components and 73 liaisons removed. The modular design significantly reduces disassembly time for mostly external panels and other high-value parts, which are typically recovered first.

5. Conclusions

The paper presented a test of a time-based methodology and a related software tool (LeanDfD) for disassemblability assessment through two case studies: an electric blender and a soda vending machine. The disassembly times estimated by LeanDfD for the electric blender case study were primarily compared with those obtained from an experimental test. The average deviation between calculated and measured times is 7.9% (standard deviation 4.7%). These values are consistent with those reported in previous studies utilizing virtual prototypes. In [20], the authors employed DELMIA to analyze the disassembly of an internal combustion engine, reporting a deviation of 7.1% between simulated and experimental disassembly times. In [21], a modified Boothroyd and Dewhurst method was applied to a set of toy products, with the discrepancy between theoretical and manual disassembly times found to be approximately 4.3%.

In the vending machine redesign project, the LeanDfD tool was employed to assess its effectiveness in identifying disassembly constraints and guiding design improvements. Implementing the redesign recommendations generated by LeanDfD led to a substantial improvement, reducing disassembly time by approximately 20% for the selected target components.

There are a few limitations associated with the LeanDfD tool that should be considered. First, the tool tends to underestimate disassembly time because it does not account for factors such as hidden accessibility, handling precautions, and ergonomic access. Second, the tool relies on the availability of reference model data, which is typically accessible only within the context of product redesign projects. Consequently, for a new product design, an initial model is required before applying LeanDfD for disassembly optimization. Third, the current liaison classification system, although effective for the analyzed case studies, needs further refinement to support broader applicability across diverse industrial sectors (e.g., structures, plants).

Acknowledgements

This research was funded by the MUR Call for proposals n. 104 of 02-02-2022- D.D. n. 1401 of 18-09-2024 PRIN2022 Scorrimento - ERC sector PE8 - Project title: DiDaMi - A knowledge-based Design for Disassembly methodology using a Data Mining approach - Project Code 202289H7B2 - CUP Code D53C24003900001

References

[1] C. Favi, M. Germani, M. Mandolini, M. Marconi, Includes Knowledge of Dismantling Centers in the Early Design Phase: A Knowledge-based Design for Disassembly Approach, in: Procedia CIRP, 2016: pp. 401–406. https://doi.org/10.1016/j.procir.2016.03.242.

[2] S. Kumar, V. Putnam, Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors, Int J Prod Econ 115 (2008) 305–315. https://doi.org/10.1016/j.ijpe.2007.11.015.

[3] P. Vanegas, J.R. Peeters, D. Cattrysse, P. Tecchio, F. Ardente, F. Mathieux, W. Dewulf, J.R. Duflou, Ease of disassembly of products to support circular economy strategies, Resour Conserv Recycl 135 (2018) 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022.

[4] R.A. Raja Ghazilla, N. Sakundarini, Z. Taha, S.H. Abdul-Rashid, S. Yusoff, Design for environment and design for disassembly practices in Malaysia: a practitioner's perspectives, J Clean Prod 108 (2015) 331–342. https://doi.org/10.1016/j.jclepro.2015.06.033.

[5] A. Desai, A. Mital, Evaluation of disassemblability to enable design for disassembly in mass production, Int J Ind Ergon 32 (2003) 265–281. https://doi.org/10.1016/S0169-8141(03)00067-2.

[6] M. Goosey, End-of-life electronics legislation – an industry perspective, Circuit World 30 (2004) 41–45. https://doi.org/10.1108/03056120410512235.

[7] D. O'Rourke, The science of sustainable supply chains, Science (1979) 344 (2014) 1124–1127. https://doi.org/10.1126/science.1248526.

[8] M.C. Majmundar, N.A. Zulfiquar, Design for Disassembly to Attain Sustainability: Analyzing the Past and Proposing Further Research Opportunities, The IUP Journal of Supply Chain Management XV (2018) 37–76.

[9] E. Kissi, M. Ansah, J. Ampofo, E. Boakye, Critical Review of the Principles of Design for Disassembly, Modular and Offsite Construction (MOC) Summit Proceedings (2019) 251–258. https://doi.org/10.29173/mocs101.

[10] S. Sadraee, A case study on Design for disassembly, its application in building design and potential for component reuse and material recycling to mitigate construction waste, Université du Québec à Montréal, 2020.

[11] C.M. Rose, K. Ishii, A. Stevels, Influencing Design to Improve Product End-of-Life Stage, Res Eng Des 13 (2002) 83–93. https://doi.org/10.1007/s001630100006.

[12] Y. Pnueli, E. Zussman, Evaluating the end-of-life value of a product and improving it by redesign, Int J Prod Res 35 (1997) 921–942. https://doi.org/10.1080/002075497195452.

[13] C. Favi, M. Marconi, M. Germani, M. Mandolini, A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling, Advanced Engineering Informatics 39 (2019) 62–79. https://doi.org/10.1016/j.aei.2018.11.008.

[14] C. Favi, M.G. Mandolini, M. Marconi, LeanDfd: A design for disassembly approach to evaluate the feasibility of different End-of-Life scenarios for industrial products, in: Leveraging Technology for a Sustainable World - Proceedings of the 19th CIRP Conference on Life Cycle Engineering, 2012. http://www.scopus.com/inward/record.url?eid=2-s2.0-84926209356&partnerID=MN8TOARS.

[15] M. Germani, M. Mandolini, M. Marconi, M. Dufrene, P. Zwolinski, A Methodology and a Software Platform to Implement an Eco-Design Strategy in a Manufacturing Company, in: Volume 4: 18th Design for Manufacturing and the Life Cycle Conference; 2013 ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications, Portland, Oregon, 2013: p. V004T05A039. https://doi.org/10.1115/DETC2013-12974.

[16] M. Germani, M. Mandolini, M. Marconi, A. Morbidoni, M. Rossi, Eco-Design Platform Within an Extended Enterprise: How to Implement It?, in: Volume 4: 19th Design for Manufacturing and the Life Cycle Conference; 8th International Conference on Micro- and Nanosystems, ASME, Buffalo, NY, USA, 2014: p. V004T06A046. https://doi.org/10.1115/DETC2014-34340.

[17] M. Germani, M. Dufrene, M. Mandolini, M. Marconi, P. Zwolinski, Integrated Software Platform for Green Engineering Design and Product Sustainability, in: A.Y.C. Nee, B. Song, S.-K. Ong (Eds.), Re-Engineering Manufacturing for Sustainability-Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013, Springer Singapore, 2013: pp. 87–92. https://doi.org/10.1007/978-981-4451-48-2_14.

[18] C. Favi, M. Germani, M. Mandolini, M. Marconi, Promoting and Managing End-of-Life Closed-Loop Scenarios of Products Using a Design for Disassembly Evaluation Tool, in: Volume 3: 38th Design Automation Conference, Parts A and B, ASME, Chicago, Illinois, USA, 2012: p. 1339. https://doi.org/10.1115/DETC2012-70997.

[19] M. Mandolini, C. Favi, M. Germani, M. Marconi, Time-based disassembly method: how to assess the best disassembly sequence and time of target components in complex products, The International Journal of Advanced Manufacturing Technology 95 (2018) 409–430. https://doi.org/10.1007/s00170-017-1201-5.

[20] K. Cai, W. Zhang, J. Li, H. Zhao, Maintenance Time Measurement for Mechanical Products Based on Virtual Prototype, Instrumentation Mesure Métrologie 18 (2019) 15–23. https://doi.org/10.18280/i2m.180103.

[21] Y. Hu, G. Ameta, A Charts-Based Approach to Estimate Disassembly Time: Hypothesis, Model and Validation, J Manuf Sci Eng 141 (2019). https://doi.org/10.1115/1.4042107.