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Original
Integrating Circular Strategies into Product Concept Design: A Proxy-Based LCA Approach Within the MBSE Framework / Brusa, Eugenio; Gastaldi, Chiara; Hierro Magnet, Monica. - ELETTRONICO. - (2025), pp. 1-8. (2025 IEEE International Symposium on Systems Engineering (ISSE) Palaiseau (FRA) 28-30 October 2025) [10.1109/ISSE65546.2025.11370052].

Publisher:
IEEE

Published
DOI:10.1109/ISSE65546.2025.11370052

Integrating Circular Strategies into Product Concept Design: A Proxy-Based LCA Approach Within the MBSE Framework

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***Abstract*—Planet eco-mourning motivates assuring full sustainability to new industrial products. This requires implementing circular economy within the product lifecycle development. Modularity, maturity and available standards candidate the Model-Based Systems Engineering (MBSE) to this purpose. This paper defines details of the integration between design for sustainability and MBSE. Environment is assumed as a primary stakeholder, alongside customer, producer, and regulatory bodies. Qualitative tools, like the LIDS Wheel and Eco-checklists, identify sustainability-related requirements, but designer must clearly prioritize competing circular strategies, such as recycling, reuse, remanufacturing, and refurbishing, for life extension. Novelty of proposed approach consists in applying a proxy-based Life Cycle Assessment (LCA). It allows comparing quantitatively circular strategies, even in the early design stage. Two steps are foreseen, i.e. quantitative LCA investigates representative reuse and recycling scenarios, and then methodology is generalized to support strategic decision making within system eco-design. Two case studies are exploited to show beneficial effects of integrated sustainable MBSE, as solar panels and internal combustion engine.**

Keywords—Eco-design, Circular design, MBSE, System Design, Life Cycle Assessment.

I. INTRODUCTION

Current trend in applying principles of the circular economy to industrial product design [1] requires integrating environmental needs [2] into the product lifecycle development [3], since the early stage of concept design. However, industrial practice still prioritizes system functionality, cost, and manufacturability, while sustainability remains an afterthought or, at least, it is addressed only once that detailed design synthesis is available. The Model-Based Systems Engineering (MBSE) methodology [4,5] provides a structured and standard framework to embed environment as a core stakeholder in the requirement analysis, alongside typical actors, as customer, manufacturer, and regulatory bodies [2]. Moreover, sustainability is associated to regeneration, into an eco and circular design combined approach. Not only waste and environmental impact are reduced [6], but resources are preserved, through a combined action of reuse of system components and recycling of materials [7].

This paper frames the environment as an additional and critical stakeholder, in the product lifecycle development, to cope with the lack of standardized design workflows, integrating MBSE and circular design [8]. It aims at introducing some practical tools and procedures, to anticipate at concept design abstraction the issues of sustainability and regeneration. They are highlighted by the European 'Ecodesign for Sustainable Products Regulation (ESPR)' [9], but related engineering methods are not yet clearly deployed. Some qualitative approaches are available, but more quantitative ones providing some clear metrics to support decision making are applied only when the system layout has been defined, more than to perform the trade-off of technological solutions. Such qualitative tools are, for instance, the LIDS Wheel [10,11,12] or the Eco-checklists [13,14,15] as they are applied even in several domains, as in the automotive engineering [16,17,18]. Those tools can drive the designer, supporting the elicitation of requirements related to sustainability, but do not help in selecting suitable strategies, by metric, especially in complex or safety critical products design, at concept stage [19].

To drive the designer in choosing between multiple and competing circular strategies, and prioritizing them, quantitative approaches are needed even at functional modelling level, when system layout has to be defined. The Life Cycle Assessment (LCA), as well as the Life Cycle Cost Analysis (LCC), is a consolidated method [20,21] for assessing environmental impact, although it is usually applied to advance stages of design activity, after the so-called design synthesis. To overcome this limitation, a proxy-based LCA methodology that leverages data from existing products to evaluate the potential effectiveness of different eco-design strategies is here introduced, and applied to two typical test cases as solar panel and internal combustion engine.

II. DESIGN FOR SUSTANIBILITY AND INTEGRATION OF END-OF-LIFE STRATEGIES FOR REGENERATION

As it was already introduced in some previous contributions [1,22], three are the main actions required to update the MBSE approach to include sustainability and regeneration within the industrial product development, as follows.

(1) Process of the product lifecycle development must be extended, i.e. instead of being limited to path from customer needs identification to product disposal, including design and manufacturing (usually represented as a 'V' diagram [1]), it must include aftermarket and service (second 'V'), where a key role is played by system RAMS (reliability, safety, availability and maintenance) [23] and decommissioning, at the end of life (third 'V'), as in Fig.1. This one is supported by

several typical activities, being often classified as “9R”, which also define strategies of regeneration [24]. Therefore, design must care about product regeneration, since the early stage of design, i.e. selected ‘R’ actions affect requirements and trade-off analysis in the design stage.

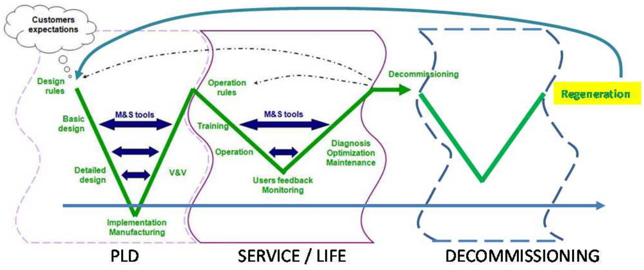

Fig. 1. Product lifecycle development extended to life and decommissioning.

(2) Requirement analysis and functional modelling must include environment as another key stakeholder. Trade-off activity is oriented to reuse and recycling, even in functional modelling and within the metamodels supported by the SysML language or equivalent [3]. This means that in simpler form sustainability-related requirements are introduced and added to other ones. In a stronger form, each requirement should include as an attribute the sustainability and regeneration targets, i.e. the impact upon those targets can be graded through a suitable scale of values. Moreover, in several diagrams, like the ‘Use Case’, environment expressively appears as a stakeholder, and all interactions and interfaces involving environment are consequently analysed (Fig.2).

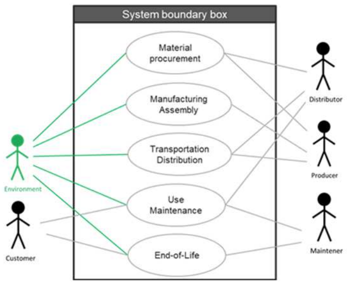

Fig. 2. Example of expressive introduction of environment as stakeholder into a Use Case Diagram depicted as the SysML language defines.

(3) Some specific analyses are required, in terms of system modelling and decommissioning, and thus typical actions of circular design must be performed and driven by a quantitative evaluation of waste, flows, emissions and resources consumption, all along the product life. Particularly, resources and energy consumption as well as waste production and emissions must be avoided or at least limited, during the design, manufacturing and life stages. This action needs introducing dedicated tools of design for sustainability [25].

Those three targets require defining some suitable tools to support related activities, as are herein detailed.

A. The ‘9R’ to be integrated inside the product development

Above-mentioned item 1 requires mastering the typical ‘R’ actions defined in the literature to support the circular design of product. As introduced by Potting et al. [26] actions are listed in Table I, where impact on the product lifecycle development is defined, within third column.

It can be remarked that those actions even describe the strategies for transition from linear to circular economy, with increasing level of regeneration, from last to first. Particularly, R9 and R8 are the lowest level of regeneration, although they already allow a preliminary circularity.

TABLE I. Main actions of Circular Design upon product

Action	***Content***	***Impact***
R0 – Refuse	Make it redundant either by abandoning its function or providing the same to a different product	To investigate alternate system functions; to exploit modularity in assembling
R1 – Rethink	Product concept should support an intensive use even in other contexts	To investigate alternate applications
R2 – Reduce	More efficiency in manufacturing and less consumption of natural resources and materials	To evaluate specific efficiency and resources consumption along the development and life
R3 – Reuse	Direct reuse by another consumer of discarded product	To facilitate reuse by monitoring residual life and making easier disassembly at the end of life
R4 – Repair	Repairing and maintenance, for same function and extended life	To design accurately RAMS issues along life and monitor residual life
R5 – Refurbish	Restoring product while making up to date	To predict obsolescence of components and monitor exploitation in service
R6 - Remanufacture	Use parts of discarded product into a new one, within the same function	To select assembling and material processing compatible with remanufacturing
R7 – Repurpose	Use parts of discarded product into a new one, with different function	To select assembling and material processing compatible with remanufacturing
R8 - Recycle	Processing materials to obtain either higher or lower grade quality	To select materials and processes compatible with recycling techniques and processes
R9 - Recover	Transformation (incineration) of material with energy recovery	To know properties for transforming without emissions, pollution, risk of toxicity

Life extension is assured by actions R7 to R3. Smarter use and manufacture of product correspond to actions R2 to R0, as they are directly implemented without a preliminary processing, as it happens for R7 to R3. Actually, actions look 10 more than 9, although ‘refuse’ is seldom obtained by design, while more often product looks so versatile to be used even accidentally within other systems and context. In this sense, it is a little bit considered aside those really predicted by design. Consequently, it might be also remarked that those actions are divided into three main groups. The first (R0 to R2) aims at minimizing need of products and increasing processes efficiency. The second one (R3 to R7) aims at extending product life. The last (R8 and R9) aims at extracting energy or assuring a second life to materials. Particularly, those strategies are supported in different ways. R0 to R1 define the design approach implemented and directly induce some specific requirements. R2 calls for a quantitative evaluation, at each level of abstraction of the design activity. According to current trends, and to the "Green deal" [27], for instance, it is somehow mandatory, as an overall design strategy, which is never competing with those of second group, while they could be among themselves. More specific actions support that group. Along system life, monitoring, prognosis and diagnosis activities are required to identify failure modes, damages and predict residual life. This is mostly based on data retrieving and elaboration, to be connected to the RAMS tools and analysis, as already detailed in [23]. In decommissioning, it is crucial the Life Cycle Assessment as key tool of investigation. In case of R8 and R9, some additional specific screening of materials properties and technologies is helpful [28-30]. In that sense, tools for decision making are specifically needed to compare and prioritize strategies R3, R5, R6, R7 and R8. This action integrates functional and physical modelling performed within the MBSE, and is herein mainly focused. As Fig.3 shows, strategies create a loop within the product lifecycle development, being differently closing upon process steps, and even exhibiting different impact.

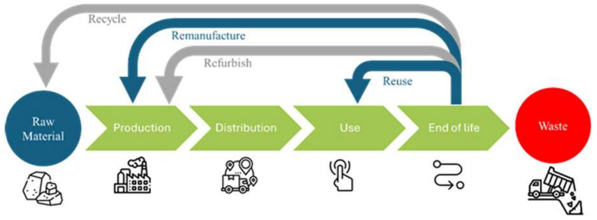

Fig. 3. Impact of main regeration strategies upon steps of the product lifecycle development.

B. Requirements elicitation related to sustainability

As actions '9R' basically apply intensively along the product development, once that they have been identified and selected for implementation, they have immediate impact upon design approach and consequently excite the elicitation of some specific requirements. Therefore, above-mentioned item 2 is supported by the literature, through the definition and implementation of the so-called "Design for X" approaches. According to strategies selected among the 'Rs', some main targets are pursued along the design activity. That classification helps the designer in adding dedicated requirements within typical classes as functional, operational, architectural [3] and other ones, being eventually and expressively introduced in several technical domains. A brief example is that of the AGV (Autonomous Guided Vehicle) [31] being exploited to transport payloads inside a factory. It is equipped with a chassis, to be usually very stiff and strong to bear the huge weight of payload. In some configurations, it is built by welding structural elements together. However, if design aims at making possible a easy disassembling for reuse, joining system should be compatible with that target. In that case, some layouts prefer bolted joints to welds, although a suitable dimensioning is required to assure the same stiffness. In the requirements elicitation, surely modularity would appear among the architectural requirements and even reversibility of joining systems as well.

The literature introduced several interpretations about the "Design for X" as described in review [32], but just to circumstantiate this topic, let's consider the main structure proposed in Fig.4, as several other detailed targets could be included in some of those depicted, at least for a preliminary screening.

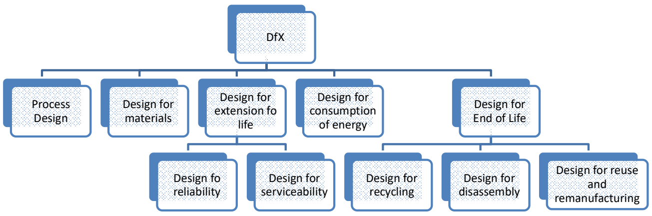

Fig. 4. Synthesis of main targets of "Design for X" approach to support the design for sustainability.

As it can be remarked, main emphasis is attributed to control process, select materials, manage power consumption and then to extend life, with two actions, i.e. along life by controlling system reliability and serviceability (RAMS) and at the end-of-life by regenerating. All those targets are assumed as promoters in the requirements elicitation, but still a clear policy to prioritize them is missed.

C. LCA as a leverage for quantitive evaluation and prioritarization of regeneration strategies

According to above cited item 3, analyses are required to be able to prioritize strategies and actions. As in case of RAMS analyses, along the concept design stage several information are not yet available to perform a quantitative investigation. Nevertheless, for RAMS it is possible to perform a Failure Hazard Analysis [23], which simply negates system functions and investigates effects upon the system behaviour, and precisely calculates the system reliability, once that system design has been completed. Similarly, in the LCA a preliminary estimation of impact could be performed by resorting to systems and products with comparable scale and properties, which look nicely proxy. Therefore, the Proxy-based LCA analysis can be implemented. It allows evaluating options and driving designer towards a preferred layout and trade-off to be verified by a second LCA based upon the real properties of physical components selected by design.

To perform that analysis are required the LCA method and some software tool to enrich the tool chain already composed to implement the MBSE as in [33]. To clarify this implementation, a couple of examples looks helpful, i.e. evaluation of the LCA of solar panels and of an internal combustion engine, in the perspective of prioritizing reuse, recycling, remanufacturing, refurbishment strategies at the end of life.

III. THE PROXY-BASED LCA APPROACH APPLIED TO TEST CASES

To cover the two specific approaches of "design for extension of life" and "design for end-of-life" models, being developed within requirements management, functional modelling and numerical modelling, tools need to be integrated with a LCA tool management. To clarify its use both at concept and development levels, two test cases have been selected and are herein briefly described.

A. The LCA analysis

The LCA is a standard tool fulfilling requirements of standard ISO 14040 and aims at assessing for a product or service environmental impact at medium and long term [34]. It proceeds through four main steps:

1. objectives and boundaries are defined in the ‘Purpose and Scope of the Investigation’
2. inputs and outputs are quantified in the ‘Life Cycle Inventory Analysis’
3. environmental impacts are evaluated in the ‘Life Cycle Impact Assessment’
4. key impacts are detected and conclusions are expressed in the ‘Life Cycle Interpretation’.

B. *Software tools*

Some commercial software tools already support that investigation, namely the Ecochain® and Ecoinvent®. Ecochain®, in accordance to ISO 14040 deploys the LCA analysis and helps the designer in quantifying, comparing, and improving environmental performance, through an informed decision-making path, to develop sustainable products and processes. Ecoinvent® is a Life Cycle Inventory Data base and provides comprehensive data on various key impact categories including carbon footprint (CO_2 emissions), water consumption, energy usage, material consumption, pollution data such as air, water, and soil emissions and waste generation and management. They drive the designer in modelling the life cycle of product, from raw material extraction to end-of-life, and in calculating environmental impacts and carbon footprint (kgCO_2 eq). Evaluation of the sustainability benefits brought by the application of Circular Design strategies are investigated by defining some scenarios and then comparing figures to identify the most sustainable options among those proposed.

C. *Test cases*

A typical example of solar panel has been selected in the commercial literature as first example. It consists of the Victron Energy 115 Wp/12V. It is made of Polysilicon material, its dimensions are 1015x668x30 mm, weight is 8 kg, cells per module are 36. The electric performance is guarantee along 10 years up to 90%, and along 25 years up to 80%, but no longer. Maximum power reaches 115 Wp (Watt-peak). Tolerance on data is 0 to 3%. Second test case consists of the Diesel engine SINOT-RUCK WD615.87A, whose properties are 9.726 l of displacement, 213 kW of rated power, 2100 rpm of rated speed, 1160 Nm of maximum torque, 900 kg of net weight and volume corresponding to 1534x675x1166 mm.

In the following simulations, it is assumed that the designer, along the product lifecycle development, and according to functional, operational and architectural requirements, identifies a preliminary scale and layout of product, by logical analysis, i.e. specific commercial components and subsystem are not yet identified, as they would be after the physical analysis [3], but technological options are defined to perform the trade-off analysis. In that sense, if a proxy product is selected as the two ones used as test cases, related analyses deploy as follows.

D. *Test 1: recycling*

Purpose and scope: the first test case is exploited to simulate a comparison between option of manufacturing a new solar panel (scenario 1) and recycling up to 65% (feasible according to literature [35]) of raw material composing that product, and recycling discarded materials to produce a new unit (scenario 2). The goal is investigating the reduction of carbon dioxide emission related to recycling.

Life Cycle Inventory Analysis: input data for raw materials exploited in building the solar panel were retrieved from [36]. The energy and materials required to build and operate the machinery used for extracting and transporting raw materials have been neglected, for lack of information. Ecochain® was used to predict kgCO_2 equivalent to produce a new panel by simulating the whole LCA as in [37]. Results are shown in Table II.

TABLE II. COMPARISON BETWEEN NEW PRODUCTION AND RECYCLING 65% OF MATERIALS

Raw material	kg	kgCO2 eq (new)	kgCO2 (65% recycled)
Aluminium	0.75	7.42	3.14
Solar glass	5.92	39.36	16.63
Silicone	0.21	0.15	0.06
EVA	0.6	1.1	0.46
Tedlar	0.007	0.00007	0.00003
Copper	0.035	0.00545	0.0023
Silver	0.012	0.00802	0.00339
Lead	0.0033	0.00001	6.22e-6
Plastics	0.495	0.17	0.07
Tin	0.005	0.0005	0.00021
Paper	0.0018	3.21e-6	3.76e-6
New Product	**7.95**	**48.21**	
Recycled (65%)	**5.17**		**20.37**

Life Cycle Impact Assessment: calculations have been then performed in case of recycling of 65% of raw materials and reported in fourth column of Table II.

Life Cycle Interpretation: As results show, comparing scenario 1, in which current exploitation of raw materials has been assumed, to scenario 2, where materials are recycled up to 65%, impact difference approximately corresponds to 27.84 kgCO_2 eq., i.e. 57,7% of value for a new product. Result looks appreciable, provided that other sources currently neglected could have a similar impact in the two scenarios considered.

E. *Test 2: reuse*

To simulate the need of prioritizing either reuse or materials recycling of solar panel a second investigation could be performed, about reuse of components.

Purpose and scope: the same test case is analysed. Three scenarios are assumed. As manufacturer observed, after 10 years the solar panel is still active, although efficiency looks degraded. Therefore, it looks worth calculating carbon dioxide impact for manufacturing a new product (scenario 1), to extend its life of 10, 15, 20 and 25 years (scenario 2), and to replace it by new product, every 10 years (scenario 3).

Life Cycle Inventory Analysis: Ecochain® already estimated in test 1 the kgCO_2 equivalent to produce a new panel as 48.21 kgCO_2 eq. This is the total amount for given product.

Life Cycle Impact Assessment: If the same panel remains in service, i.e. is never replaced, along 10, 15, 20, and 25 years that amount of Carbon dioxide is spread over a longer time, with beneficial effects. Particularly, 48.21 kgCO_2 eq correspond to 4.82, 3.21, 2.41 and 1.93 kgCO_2 eq. per year, respectively, for each life extension considered. It means that from 10 to 15 years annual impact decreases by 33%, from 15 to 20 by 25%, from 20 to 25 years by 20%, with respect to previous value. For the whole range of time, from 10 to 25 years, annual impact decreases by 60%, i.e. it is only 40% of initial value. Replacing every 10 years the solar panel requires manufacturing a second unit to cover 20 years, and a third one to cover 25 years. Replacing unit every 10 years over 20 corresponds to 96.42 kgCO_2 eq. and over 25 to more than 120.52 kgCO_2 eq., assuming that third unit will remain in service still for 5 years. Trend is depicted in Fig.5.

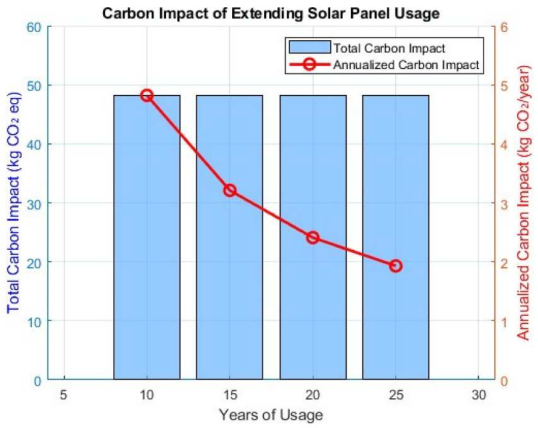

Fig. 5. Evaluation of Carbon dioxide impact with extended life of solar panel.

Life Cycle Interpretation: As results show, over 25 years, reusing the same unit in terms of emissions reduces impact of 60%, although it must be considered that electrical efficiency is lower, materials aging could be a problem and reliability must be verified. Nevertheless, in terms of LCA, if one compares options of recycling after 10 years at 65% to produce a new unit, that of reusing for 20 years the same unit, and replacing the unit after 10 years with a new one, impacts look like 68.58, 48.21, 96.42 kgCO_2 eq. Reuse looks a possible option to be prioritized, although additional evaluations about RAMS and electrical efficiency should be added.

F. *Test 3: remanufacturing*

Second test case was exploited to investigate a comparison between remanufacturing and refurbishment strategies. Particularly, remanufacturing is emerging as a key approach in the automotive industry. This process extends the lifespan of existing vehicle components, retains the inherent value of decommissioned parts, and reduces the need for additional raw materials and the environmental impact associated with producing new components. Unlike other end-of-life treatments, such as repair, downgrading, or reconditioning, remanufacturing restores end-of-life products or components to a condition that is as identic to original product. The typical remanufacturing process involves collecting end-of-life products or cores, followed by several key stages, including disassembly, cleaning, inspection, repair of defective parts, replacement of non-reusable components, reassembly, and final testing.

Purpose and scope: two scenarios herein compared are the manufactured Diesel unit, as a new product (scenario 1), and the Diesel engine remanufactured (scenario 2), removing damaged areas from components, and replacing severely degraded parts with new ones. Data for the LCA have been retrieved from [38]. They refer to up to 100 units of the Diesel engine SINOT-RUCK WD615.87A. It is widely used in heavy-duty trucks and large cargo transport vehicles.

Life Cycle Inventory Analysis: the manufacturing of that engine has been identified through its life cycle, which looks like in Fig.6. The input data of raw materials and weight used for manufacturing that engine are collected in Table III.

TABLE III. COMPONENTS LIST OF DIESEL ENGINE

Components	***Raw material***	***Weight (kg)***
Cylinder block	Cast iron	260
Cylinder head	Cast iron	93.6
Crankshaft	Alloy Steel	103
Connecting rod	Alloy Steel	21.1
Camshaft	Alloy Steel	11.25
Valve	Alloy Steel	2.1
Tappet	Alloy Steel	3.15
Injector	Alloy Steel	2.22
Injection pump	Cast aluminum	9.65
Compressor	Alloy Steel	19.4
Turbo Charger	Cat aluminum and iron	20
Gear chamber	Cat iron	22.1
Flywheel cover	Cast iron	43.65
Oil pan	Steel	9.35
Exhaust pipe	Cast iron	21.05
Intake pipe	Cast aluminum	8

In this case, for scenario 1, the average trucking distance to transport material for producing a new unit is 880 km. The average energy consumption of the production of 100 engines is 230 kwh. In operation, it is estimated that engine drives the truck along 300.000 km. At the end-of-life, engine is transported to a dismantling plant, at a distance of 50 km, to be disassembled. It is estimated that compressed air used for disassembling is up to 30 m^3 and power is 2 kWh.

For scenario 2, remanufacturing is conceived as in Fig.7. According to sources [38,39] to assure a high reliability of remanufacturing, some professional engine remanufacturers are involved, at an average transportation distance of 800 km. Disassembling, cleaning, and inspection are carried out in the evaluation place. Disassembled parts are classified into three categories as directly-reused, re-manufacturable and replacement parts. Required inputs are known. Compressed air for disassembling is up to 3000 m^3. Resources for cleaning are electric power, 3381 kWh, kerosene fuel, 880 kg, and water, 1097 kg. Inspection even requires electric power, 1783 kWh.

The inventory data for re-manufacturable parts include precise machining to fulfil the same standard requirements as new parts, in terms of dimensions, surface roughness, and other properties. Machining time and equipment power allow calculating the energy consumption, during processes. Inputs used by Ecochain® are electric power for repairing and/or restoring parts, 6473 kWh, Diesel fuel, 1304 kg, kerosene, 81 kg, Cast Iron, 810 kg, and water 972 kg. For reassembling process, are required electric power, 19083 kWh, Cast Iron, 7475 kg, alloy 8897 kg, aluminium, 2750 kg, and rubber, 650 kg. Testing and packaging use electric power, 200 kWh, and Diesel fuel, 500 kg. As quality and performance of remanufactured engines are equal to those of new product, it is assumed that their service covers 300.000 km of trucking distance. At the end of life, disassembling and materials recycling are performed, with trucking distance to reach the dedicated plant of 50 km, and are required electric power, 200 kWh, and compressed air, 3000 m^3.

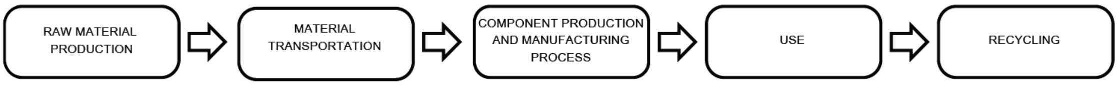

Fig. 6. Schematic life cycle of Diesel engine used as second test case.

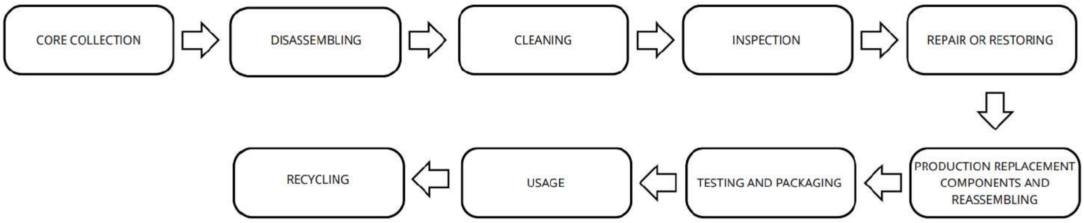

Fig. 7. Schematic remanufacturing process of Diesel engine used as second test case.

TABLE IV. EMISSIONS FOR NEW PRODUCT MANUFACTURING

Life cycle phase	***kg CO_2 eq***
Raw materials production	569.000.000
Materials transportation	278.462
Component production and manufacturing process	11.000.000.000
Use / Service	26.400.000.000
Recycling	993
TOTAL IMPACT	**37.969.279.455**

TABLE V. EMISSIONS FOR REMANUFACTURED PRODUCT

Life cycle phase	***kg CO_2 eq***
Core collection	230.134
Disassembling	9.208
Cleaning	633.984
Inspection	940
Repair and restoring	1.576.931
Production replacement components and reassembling	9.503.011
Testing and packaging	205.631
Use / Service	26.400.000.000
Recycling	10.213
TOTAL IMPACT	**26.412.170.052**

Life Cycle Impact Assessment: All data collected are inputs for Ecochain® which predicts the Carbon dioxide emission related. Particularly, for scenario 1 results are described in Table IV. For scenario 2, results are described in Table V.

Life Cycle Interpretation: As results show, total impact for scenario 1, i.e. for a new manufacture of Diesel engine, is $3.8\ 10^{10}$ kg CO^2 eq. versus value for scenario 2, reaching $2.64\ 10^{10}$ kg CO^2 eq. Remanufacturing assures a reduction of 30.47% in environmental impact, and thus looks beneficial.

G. *Test 4: refurbishment*

It is worth comparing results of remanufacturing to refurbishment, in this last test. Refurbishment refers to modifying a product, as a part of maintenance or intermediate repair process, to restore or enhance its performance and functionality, ensuring that it meets relevant technical standards. The goal is to produce a fully operational product that can serve at least its original intended purpose [40-42]. Unlike remanufacturing, where all components are replaced and reassembled, refurbishment is not as extensive as remanufacturing, but it aims at extending the product lifespan. Refurbishment involves repairing only the faulty parts and the process can range from basic testing and extensive cleaning to repairing the damage components of the product. Main difference between refurbished and remanufactured product is that refurbishment repairs product to function, but does not assure to look as the new one, while remanufactured matches completely with new product.

Purpose and scope: The goal is elaborating and then evaluating, by means of Ecochain®, the carbon footprint of the refurbishment and remanufacturing life cycles of that Diesel engine and, finally, comparing the two scenarios.

Life Cycle Inventory Analysis: First at all, the refurbishment strategy proposed is identified. It looks like in Fig.8.

As in previous test, several data are collected. For refurbishment, trucking distance is 800 km; cleaning: electric power 3381 kWh, kerosene 880 kg, water 1097 kg, inspection power 1783 kWh; repairing: power, 6473 kWh, Diesel fuel, 1304 kg, kerosene, 81 kg, Cast Iron, 810 kg, water, 972 kg. For testing and packaging are required power 200 kWh, and Diesel fuel, 500 kg. For remanufacturing, transportation distance is 800 km, compressed air for disassembling, 3000 m^3, cleaning: electric power, 3381 kWh, kerosene, 880 kg, water 1097 kg, inspection electric power, 1783 kWh. For repairing electric power is 6473 kWh, Diesel fuel, 1304 kg, kerosene, 81 kg, Cast Iron, 810 kg, and water 972 kg. For re-assembling process, are required electric power, 19083 kWh, Cast Iron, 7475 kg, alloy 8897 kg, aluminium, 2750 kg, and rubber, 650 kg. Testing and packaging use electric power, 200 kWh and Diesel fuel, 500 kg.

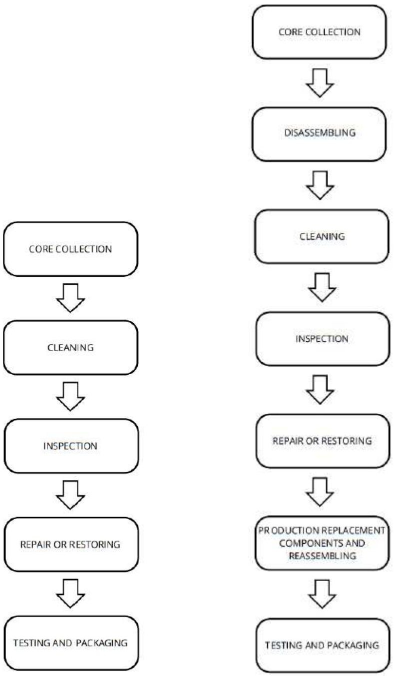

Fig. 8. Schematic refurbishment process (left) compared to remanufacturing process (right) of Diesel engine used as second test case

Life Cycle Impact Assessment: the carbon dioxide emissions for the two scenarios are described in Table VI and VII, for same usage of product.

TABLE VI. EMISSIONS FOR REFURBISHED PRODUCT

Life cycle phase	***kg CO_2 eq***
Core collection	230.134
Cleaning	633.984
Inspection	940
Repair or restoring	1.576.931
Testing and packaging	205.631
TOTAL IMPACT	**2.647.620**

TABLE VII. EMISSIONS FOR REMANUFACTURED PRODUCT

Life cycle phase	***kg CO_2 eq***
Core collection	230.134
Disassembling	9.208
Cleaning	633.984
Inspection	940
Repair or Restoring	1.576.931
Production replacement components and reassembling	9.503.011
Testing and packaging	205.631
TOTAL IMPACT	**12.159.839**

Life Cycle Interpretation: In this case, refurbishment leads to have an amount of 2.65 10^6 kg CO^2 eq. while the remanufacturing brings to 1.22 10^7 kg CO^2 eq. even considering that here use of system has been assumed to be equal, and disregarded in that comparison. Difference corresponds to 78.23% lower emissions in case of refurbishment. In that sense, prioritizing refurbishment is an outcoming indication for product development, at least in terms of regeneration strategy.

H. Tool chain integration

The above-mentioned analysis has been based on the Ecochain® and Ecoinvent® software, although some elaborations have been performed by means of Excel® sheets or the Matlab® environment. Those tools add to a number of other tools already composing a typical tool chain of the MBSE [43]. A demonstration of full interoperability between those tools with functional and physical modelling tools and of compliance to orchestration, either performed by the Ansys ModelCenter® or Dakota software®, must be provided. Nevertheless, data extraction looks sufficiently easy that a real co-simulation does not look required, if orchestrator can manage the interaction together with those dedicated software tools, during the trade-off analysis. Furthermore, the integration of optimization frameworks, such as the Dakota® software, paves the way toward a true multidisciplinary design optimization (MDO), thus transforming the tool herein presented from an environmental sustainability estimator into a comprehensive decision-support platform. This would enable the simultaneous consideration of all three dimensions of sustainability (environmental, economic, and social), while aligning with the needs of multiple stakeholders, as it would be further developed in a next contribution.

Specifically, some dedicated KPIs may be defined to address those different perspectives, as follows.

(1) Economic: return-on-investment metrics for producers choosing between reuse and recycling of retired components (e.g., solar panels), or between remanufacturing and refurbishment of ageing diesel units.

(2) User-related: indicators of customer appeal, proportional to the performance and cost advantage of reused and/or remanufactured units compared to new ones.

(3) Social: metrics capturing the need for potentially hazardous treatments in recycling processes, or even the creation of new professional roles, in the reuse and remanufacturing chains.

IV. CONCLUSION

A current need of companies consists in integrating sustainability and regeneration issues within the design activity, with low impact upon tool chains and methodologies already used and low cost for operators training. The MBSE methodology looks suitable for that integration, as it is already applied in several industrial domains, is modular, mature, standard and supported by some dedicated software. Nevertheless, a consolidated approach to proceed with that integration has not yet defined. In this paper, a preliminary demonstration of use of the LCA as a key tool for analysis of sustainability and regeneration has been provided. Moreover, it can be exploited in a proxy-based way, even in the concept design stage, by exploiting figures related to existing products, to prioritize regeneration strategies, as reuse, recycling, refurbishment and remanufacturing. Test cases show that is never intuitive identifying the best option, but at least a quantitative indication can be found, through the proposed approach. Interoperability and orchestration of the available software tools within the MBSE typical tool chain is a future step to be accomplished. A further extension to integrate the

LCA and LCC together within the same platform is required and is currently matter of analysis.

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