S-FMECA: A NOVEL TOOL FOR SUSTAINABLE PRODUCT DESIGN-ADDITIVE MANUFACTURING

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ABSTRACT

The choices made in the early design stage (EDS) will largely define the environmental impacts of a product. The purpose of this paper is to develop an eco-design method used for assessing semi-quantitatively the sustainability of an additively manufactured product since the EDS. This article presents a semi-quantitative method to support EDS-conscious environmental decisions. A novel Sustainable-Failure Mode, Effect, and Criticality Analysis (S-FMECA) tool is developed to support designers in the conceptual design phase, to guide the choices, and to provide a valuable evaluation of the future additively manufactured product. Through the integration of the environmental aspects in FMECA analysis, systematic prevention of errors, and enhancement of sustainability since the EDS would be the main advantage of this tool.

KEYWORDS: Design for Additive Manufacturing, environmental impact, sustainability indicators, eco-design, early design stage, failure design modes.

1. INTRODUCTION

Within the evolving context of industry, new manufacturing techniques are emerging. Additive Manufacturing (AM) is the fastest growing. Indeed, since the first patent filed in 1984 by Chuck Hull, relating to the use of stereolithography and its first 3D printer in 1986 implementing this technique, additive manufacturing has undergone a great evolution [1]. The American Society for Testing and Materials (ASTM) has classified AM processes into seven categories: powder bed fusion (PBF), material extrusion (ME), material jetting (MJ), binder jetting (BJ), sheet stratification (SS), vat photopolymerization (VP) and directed energy deposition of materials (DED). Among the applied AM technologies, we found selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), fused deposition modelling (FDM), stereolithography (SLA), direct metal laser sintering (DMLS), laser powder bed fusion (LPBF) and laser engineered net shaping (LENS).

The various types of materials are 3D printable: metals, polymers, ceramics, and composites. Even stem cells become additively manufactured: within the discovery in 2006 of human induced pluripotent stem cells (iPSCs), patient-specific stem cell lines are created from mature cell types [2].

The motivations driving the adoption of additive manufacturing encompassing product life cycle, mass customization, design complexity, and sustainability implications have been highlighted by Ahuja et al. [3]. The key challenges for the implementation of additive manufacturing in production involve different factors: strategic, technological, organizational, operational, and supply chain factors besides intellectual property implications. AM technologies have been widely seen as a non-mass production system; not only due to its build volume restrictions and slow build rates but also for the price of the raw material, and the new knowledge, in terms of configurations and set-ups, the engineers and designers must have to understand and learn [4]. Nevertheless, AM applications have progressed from rapid prototyping to the production of end-use products [5] and to a small or medium batch of customized parts [6]. Furthermore, AM techniques find very interesting applications in rapid manufacturing intended for producing tools or final products that provide long-term functionalities; also in rapid maintenance, repair, and overhaul (MRO), in which AM is utilized to repair or remanufacture defective parts [7].

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Design for Additive Manufacturing (DfAM) has become an issue to investigate the design sustainable AM products. To design for sustainable product development throughout a lifecycle vision, Lu et al. [8] suggested carrying out evaluations concerning the functional, environmental, and economic lifecycle aspects during the design process, named process-based analysis (PBA). These analyses assess the product over its lifecycle stages (Fig. 1). Initially, materials and energy are extracted from natural resources (extraction stage). Next, the materials are fabricated into product components; afterward assembled into products and packaged (production stage). Then, after being sold and distributed, the products are used (operation/usage stage), and their lifespan may be enhanced by services (repair and maintenance). The products may be routed to recycling, reuse, or landfill disposal (retirement stage).

A major number of charges accrued by an enterprise for the fabrication, maintenance, and end-of-life of products is predefined at the stage of product development. Ullman [9] mentioned that even if the decisions made during the design process cost very little (around 5% of the manufacturing cost), they have a great effect on the cost of a product (from 35% to 75% depending on the industries). Brundage et al. [10] confirmed this ascertainment by reporting that 70% to 80% of the total cost of a product is endorsed during the design stage. Correspondingly, it is assumed that a majority of the sustainability characteristics of a product are attributed during the early design stage. It follows that, throughout the product lifecycle, the ability to decrease the environmental impact of each stage reduces as the product progresses through the lifecycle. Hence, the product's cost is affected early in the design process and spent late in the process. Most research focuses on the sustainability of the manufacturing process but forsakes the impact from the design stage [11].

Chiu & Chu [12] adopted a four-step product design process: problem definition, conceptualization, preliminary design, and detail design. Several researchers [13], [14] stated that a design product framework involves three design phases: (i) conceptual design phase, (ii) embodiment design phase, and (iii) detailed design phase.

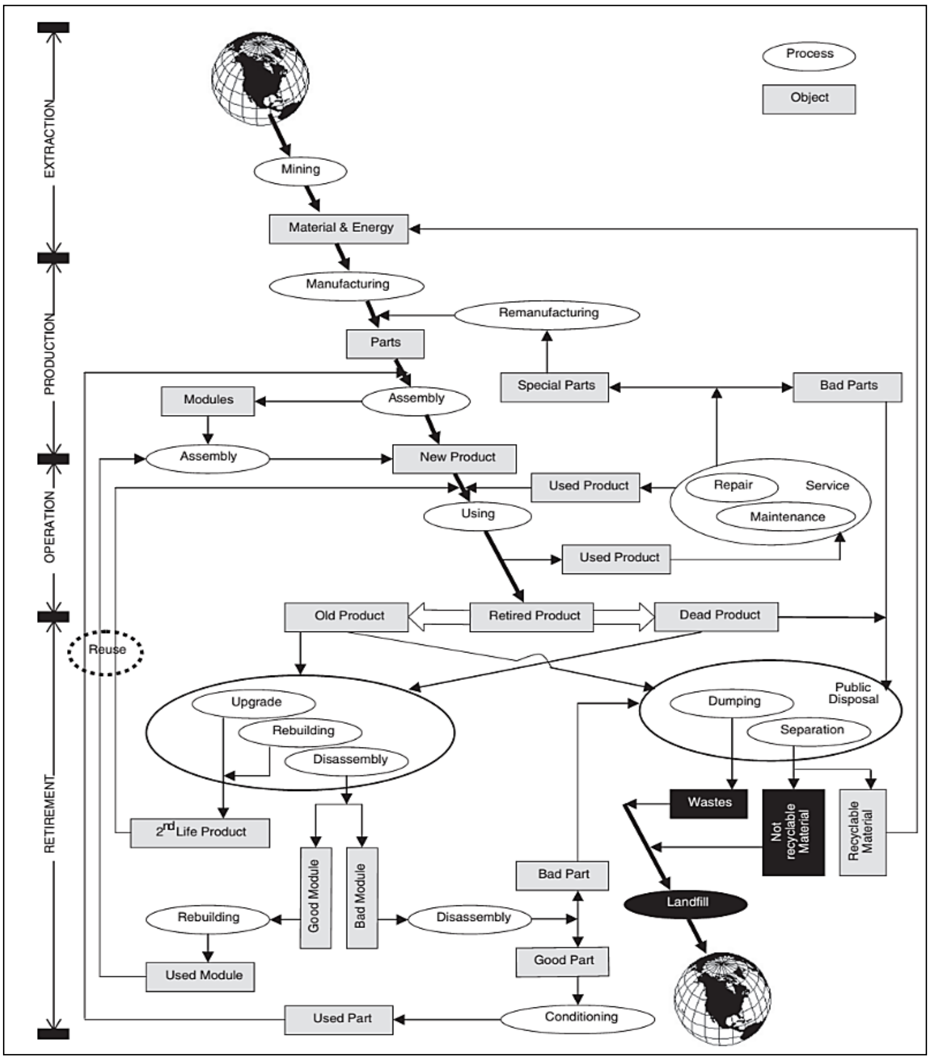

Fig. 1. Product Life Structure [8]

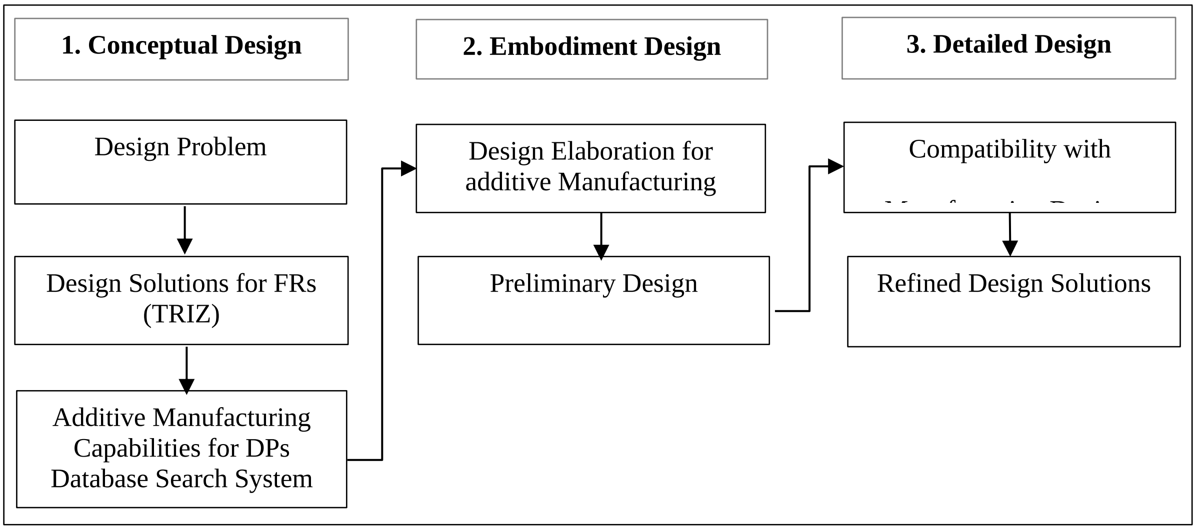

Fig. 2. Main steps of a design framework for Additive Manufacturing Design (Reproduced from [13])

In the conceptual design phase, elementary solution principles for a design problem are pointed out to derive the initial design concepts. Afterward, preliminary designs are generated in an embodiment design phase by developing the solution principles on the initial design concepts. These preliminary designs are refined in the detailed design phase. This three-phase design framework is found in literature applied to the additive manufacturing case (Fig. 2) [13]. Likewise, [14] adopted a three-step product design decomposition, named: customer needs analysis; feasibility study, and preliminary design. The author suggested using several quality tools in the product design process. These tools are:

- in the customer needs analysis utilized the Horned Beast Diagram to define the need to which the designed product answers; and the Octopus Diagram to identify the functions (principal and constraint ones);
- in the feasibility study apply the Function Analysis System Technique (FAST) diagram to present the technological solutions which allow the satisfaction of the identified functions;
- in preliminary design operate the design Failure Mode, Effect, and Criticality Analysis (FMECA) to identify all possible failures in the design.

Regardless of the variety in terminology and the number of design steps, from one researcher to another, the design needs are the same: several rules, guidelines, methods, and tools are needed to be applied in the different phases during the additive manufactured product design process. Indeed, Gebisa & Lemu [15] discussed the shift from Design for Manufacturing (DfAM) to Design for Additive Manufacturing, and the role that DfAM plays in the product development process concluded that DfAM methodologies for an optimal sustainable product design realization are quite new and not yet standardized and further investigations are needed.

In this context, Tang et al. [16] have already proposed a general framework (Fig. 3), which can integrate a design stage in Life Cycle Analysis (LCA) for reducing the product environmental impact of the AM process.

A case study demonstrated that the design optimization, using topology optimization, has a key role in reducing the environmental impact of a binder jetting AM process. While some other researchers developed a dedicated DfAM software to facilitate AM machines selection in the early design stages toward better sustainability.

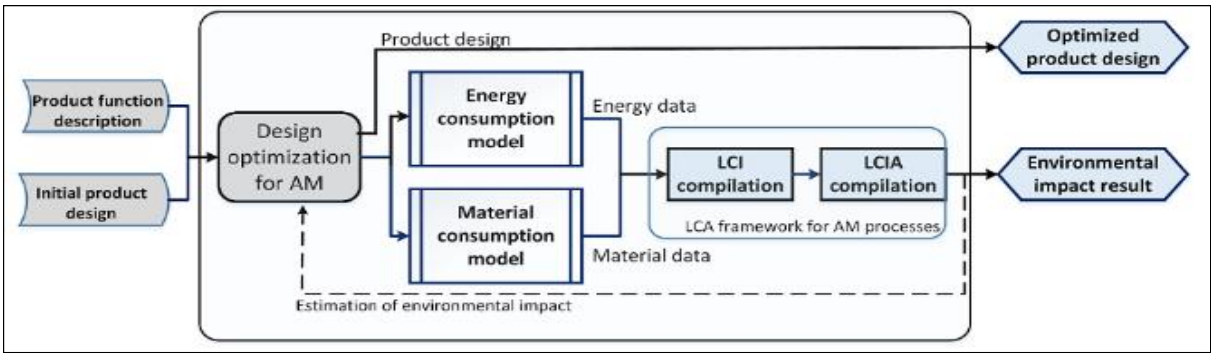

Fig. 3 General framework of environmental impact evaluation of AM [16]

Actually, Laverne et al. [17] developed a Tool for Eco Additive Manufacturing (TEAM) that optimizes environmental impact in early design stages. While Perera [18] developed a set of expert systems (MSUSTAIN1 & MSUSTAIN2) that can aid metal manufacturing facilities in selecting DMLS, BJ, or CNC Machining, considering cost-effectiveness, energy, and auxiliary material usage efficiency as the key indicators of manufacturing process sustainability.

Liu et al. [19] developed a decision-making methodology that could be integrated in the product early design stages to facilitate the AM process selection and support product/part design. Given the design requirements and using the Analytical Hierarchy Process method to evaluate and select the AM processes, the designer would identify whether the part should be designed for AM production and could select the suitable AM production system.

In addition to LCA and AM machine selection software, several authors have used other tools to improve sustainability since the early stages of the product design process, especially when designing for additive manufacturing. Specifically, the well-known tools: (i) Theory of Inventive Problem Solving TRIZ and (ii) Quality Function Deployment (QFD) usually used in the conceptual design phase have been associated with the DfAM method. Renjith et al. [13] highlighted that the existing DfAM methods have restrictions in that most methods reckon on either too general or too specific design requirements and parameters for AM. While taking into account those AM environmental considerations, the researchers succeeded in integrate axiomatic design theory and theory of inventive problem solving (TRIZ) and to propose a design framework that can effectively be used to transform original product designs for conventional manufacturing into new designs appropriate for AM. Sarath methodology enabled the decrease in the number of components, the number of welds, and the product mass. On the other side, Frizziero et al. [20] applied the Design for Six Sigma (DFSS) method to develop new products considering the “Define, measure, analyse, design, and validate” approach. Where QFD is the used tool for measuring and analyzing while, Design for AM, is the used tool in the design phase.

More recently, several authors were interested in conducting review studies to synthesize the workaround eco-design and identify the related research gaps. They concluded that eco-design tools that support design generation do not provide specific design recommendations and are highly dependent on the user’s pool of knowledge, especially for improving the environmental sustainability design implementation and interpretation [21] and that most of the existing tools and methods are difficult to learn, to understand and to use [22]. Additionally, these tools have a weak connection with the product development process and take into account only one or two stages of the life cycle [22]. As for the integration of DfAM into eco-design tools, it is still in the preliminary stage and future detailed and intensive research is required [23].

To our knowledge, eco-design methods that can consider the capabilities and constraints of additive manufacturing, and the sustainability issues at an early design stage are rare in literature, despite their necessity, especially in the conceptual design phase. As mentioned above, some attempts have already taken place to fill this gap. The present research comes to enrich the existing tools with a new one that integrates DfAM into FMECA analysis with a Life Cycle Inventory (LCI) approach. This integrated approach is effective because LCI allows a systemic product lifecycle environmental impact inventory, while FMECA can be used to prevent risks with consideration of AM capabilities and constraints.

The paper is organized as follows: first, the literature background is presented. Indeed, the three bottom line dimensions of AM processes sustainability are discussed beside the bibliographic review of the Environmental Failure Modes and Effects Analysis (E-FMEA). The subsequent section is dedicated to the proposed Sustainability-Failure Modes, Effects, and Criticality Analysis (S-FMEA) eco-design tool for AM, which is a semi-quantitative method that could be used in the early design stage. Finally, concluding remarks are given in Section 4.

2. LITERATURE REVIEW

2.1. Three-Bottom Line Dimensions of the AM Process

In a broader vision of sustainable development, some researchers have targeted the sustainability assessment of the AM process. Since the sustainability focuses on meeting the needs of the present without compromising the ability of future generations to meet their needs and the concept of sustainability is composed of three pillars (economic, environmental, and social), the three aspects should be studied.

Indeed, Ribeiro et al. [24] explored the literature on AM sustainability and mapped the results in a framework aiming to support comprehensive assessments of the AM impacts in the three-bottom line (3BL) dimensions: the People, the Planet, and the Profit. The results clearly showed the necessity for systematic analysis considering the three dimensions of sustainability and the method(s) to support it. It is then noted that, while environmental life cycle cost (LCC) and LCA are widely established methods, congruently the application of LCA techniques to social impacts introduced the notion of S-LCA. A proposal for using the S-LCA was made to a sustainability assessment framework such that the same life cycle boundaries are retained in the different dimensions of analysis. The authors suggested interviews with stakeholders and data mining techniques as tools to conduct this social LCA analysis. In terms of enhancing the environmental performance of manufacturing processes, the environmental benefits of AM, as identified by Yi [7] are: lightweighting and functional improvements, no or fewer product-specific tools and fluids, less material waste, reduction of manufacturing processes and shortening of supply chains and contribution to a circular economy (CE) strategy. Indeed, by using recycled materials for AM, and by recycling and reusing the scraps created during the production of a product in future AM processes, a closing loop strategy is implemented. Besides, during the use phase, products can be repaired by AM techniques, whereas, during the end-of-life phase, a product can be remanufactured or reused, in which case the slowing loop strategy is instigated. Khalid & Peng [25] reviewed the progress of the latest research on AM sustainability and found that energy consumption is a main contributor to the AM environmental impact (more specifically the process of electricity consumption dominated environmental impacts for almost all scenarios) whereas the design for lightweight products can effectively increase the AM sustainability. It was deplored that feedstock production and post-processing stages did not grab enough attention although they have a big impact on the assessment and that studies integrating the environmental, economic, and social dimensions are limited. Figure 4 indicates the common issues considered in research on the sustainability of AM as identified.

Looking for a detailed understanding of the AM machines' energy consumption, Liu et al. [26] investigated the AM energy consumption by breaking down the SLM machine into eight different subsystems (laser unit, powder dosage chamber, powder delivery, building platform, XY Positioning of the scanner cabinet cooling, nitrogen circulation unit, and the computer unit subsystems); and noticed that the laser is the greatest power consuming unit. Furthermore, they found out that the AM machine power energy consumption depends on the fabrication step. Indeed, the power consumption during powder spreading is the highest among the four steps: preheating, energy beam scanning, powder spreading, and final cooling down. Contrariwise, Khalid & Peng [25] proceeded with a more global approach and succeeded in summarizing the specific energy consumption (SEC), according to the additive manufacturing technique (Fig. 5).

Huang et al. [27] gave the primary energy (MJ/kg) and the carbon dioxide equivalent CO_{2e} emissions (kg/kg) for three different AM processes. It was found that the CO_2 emissions intensity is platform-dependent. Huang et al. [27] have also succeeded in making an inventory of the primary energy (MJ/kg) and the carbon dioxide equivalent CO_{2e} emissions (kg/kg) for the materials: Steel, Stainless steel, Aluminium, Titanium, and Nickel. This is for different material shapes: ingot, plate, powder, and recycled. Relatively to the economic aspect, Liu et al. [19] succeeded using a mathematical formula, in estimating the manufacturing cost per part of a component of the exhaust gas duct for several commercialized machines (Table 1).

2.2. Health and Safety of the AM Process

With an outlook to investigate the impact on human health of these evolving manufacturing processes, some authors have examined the effect of the materials used in AM more closely. Lunetto [28] emphasized that the exposure to Aluminium, Chrome, Cobalt, Nickel, Stainless steel, and Titanium metals, especially powders in the process of additive manufacturing had impacts on human health (Fig. 6). Inhalation, Oral, and Dermal are the three routes of exposure, studied by Lunetto [28], that metals, especially powders, encounter workers of production. Effects caused by the exposure to a single metal element (Aluminium, Chrome, Cobalt, Nickel, Stainless steel, and Titanium) are presented according to animal experiments and in different case studies of human exposure. The author highlighted that the cumulative effects caused by different routes of exposure, and combined effects of interaction with different elements of metal powders, are necessary to be investigated.

For the three additive manufacturing processes using metal powders (PBF, DED, BJ), the National Institute for Scientific Research (INRS) recommended the identification of the risks associated with the different products through the inventory of all incoming and outgoing products and by-products (degradation products), and this at all stages of the process. The characteristics (physicochemical, hazards, etc.) have to be identified using the available sources of information: databases, safety data sheets, toxicological sheets, etc.

Preventive actions are given [29] concerning the different types and sources of risk: the metal powder raw materials (nature, reception, reconditioning, transfer, and storage), products formed during the transformation of metal powders, inert gas, binders, maintenance/cleaning products, setting work, post-treatment and chemical hazards and the risk of fire/explosion.

In the same context, Nozar et al. [30] investigated the potential health hazards of additive manufacturing. After having identified the feedstock materials used in the seven AM categories, they noticed that, likewise plastic printing, and metal AM technologies cover a panoply of hazards. Namely fire and explosion risk, inhalation and contact of powder, inert gas asphyxiation, hazard due to electrical power, hazard due to laser radiation, thermal injury due to hot machine components and parts at the end of the building process, and during the cooling phase, and mechanical hazard of injury due to crushing or lifting of a heavy building platform.

Table 1. AM machine estimated manufacturing cost per part [19]

AM machine	AM technique	Cost per part ($)
3D Systems DMP320	SLS	343.77
3D Systems DMP500	SLS	576.87
EOSINT M290	DMLS	317.14
EOSINT M400	DMLS	525.81
GE Arcam A2X	EBM	779.63
Renishaw AM250	SLM	220.26
Renishaw AM500	SLM	516.93
SLM Solutions SLM280	SLM	277.33
SLM Solutions SLM500	SLM	540.25
Aconity One	LPBF	490.62
DMG Mori Lasertec 30 SLM	DMLS	313.87

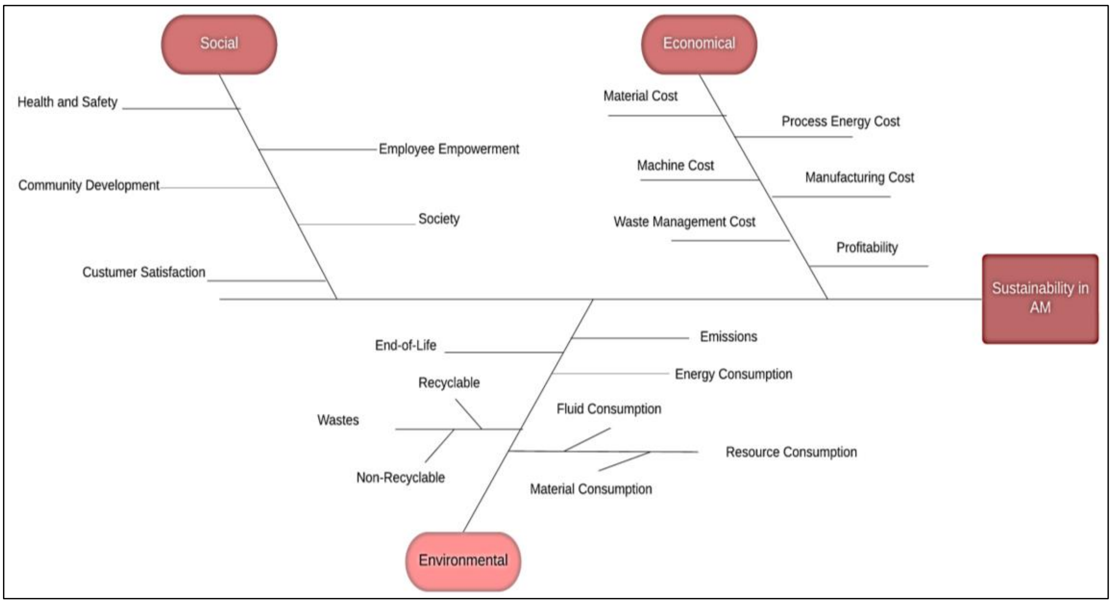

Fig. 4. Issues of AM in 3BL dimensions of sustainability (Reproduced from [25])

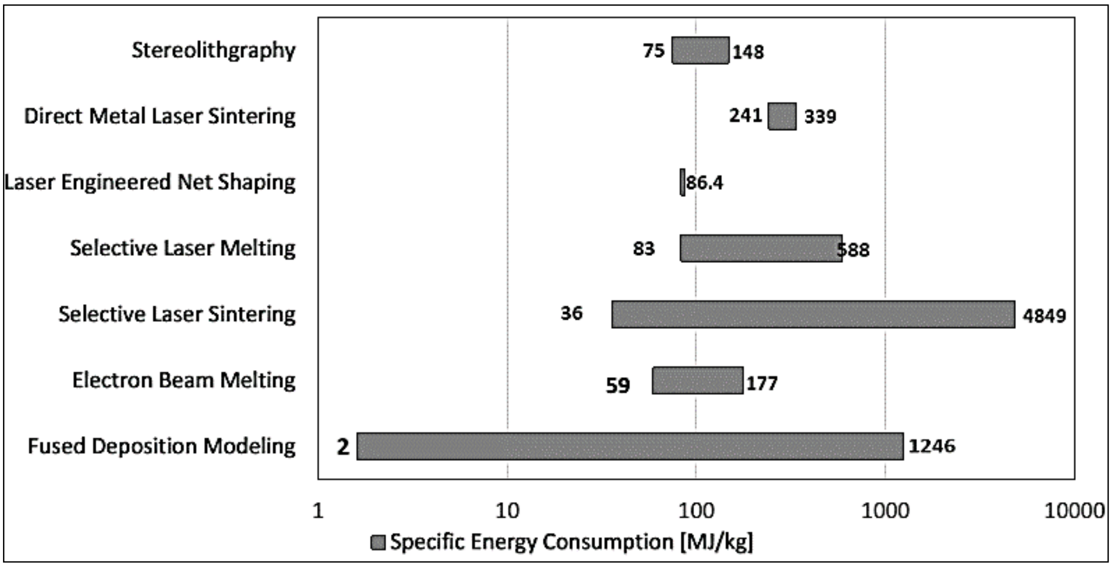

Fig. 5. SEC of different AM technologies [25]

Inhalation Exposure	Oral Exposure	Dermal Exposure
• Respiratory Effects • Cardiovascular Effects • Gastrointestinal, Musculoskeletal, Hepatic, Renal, Endocrine, Dermal, Ocular, Reproductive Effects • Hematological Effects • Body Weight Effects • Neurological Effects • Cancer	• Cardiovascular, Gastrointestinal Effects • Hematological Effects • Hepatic Effects • Renal Effects • Dermal, Ocular Effects • Body Weight Effects • Neurological Effects • Reproductive Effects • Cancer	• Dermal Effects

Fig. 6. Human safety risks - adapted from [28]

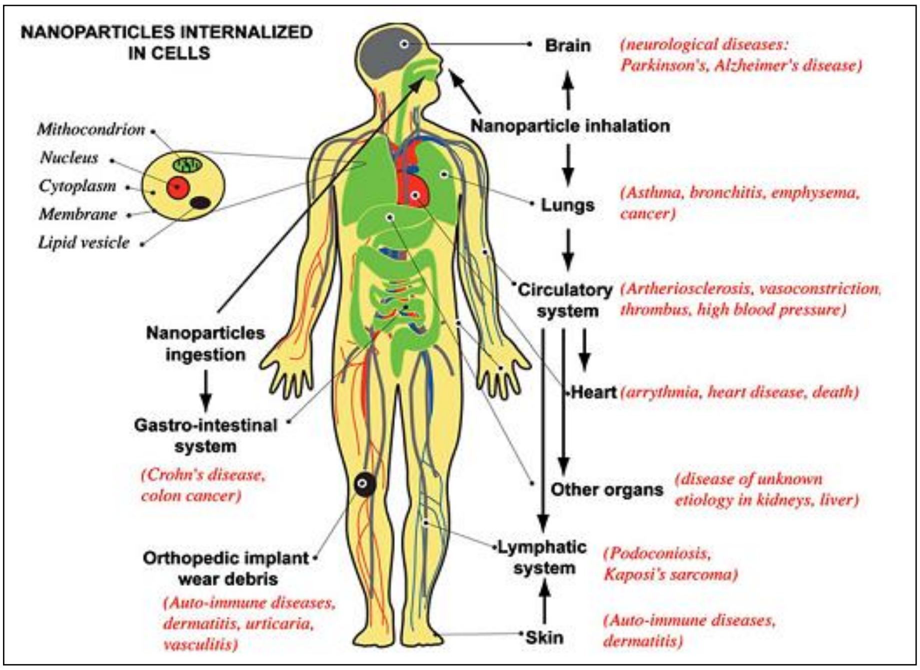

Fig. 7. Recorded diseases assigned to metal particles smaller than 1μm [31]

It was also mentioned that the effect of metal particles on human organs is still poorly studied and documented, although the inhaled particles are expected to attack different deposition locations in the human body, according to their sizes (Fig. 7).

Toxicological studies have demonstrated that toxicity is, inter alia, size-dependent, and surface-area-dependent Nozar et al. [30] as shown in figure 8.

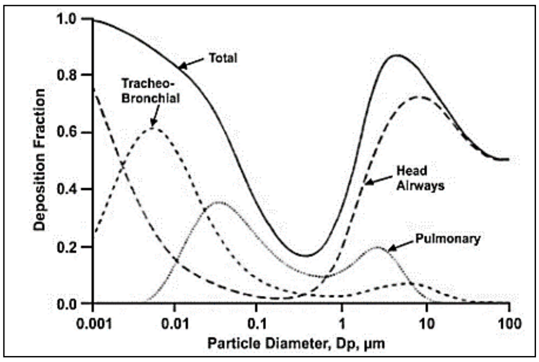

Fig. 8. Deposition fraction vs. particle diameter [30]

2.3. Environmental Failure Modes and Effects Analysis (E-FMEA)

Spreafico [32] reviewed 106 scientific papers proposing methods available in literature for over 20 years, identifying failures and assessing their hazards during eco-assessment. From the study emerged, a growing interest in the methods related to the product functioning for supporting failure risk analysis in eco-assessment by the scientific community.

In addition to the usage of tests, simulations, FMEA-based approaches, and knowledge databases to determine the failures, statistical methods are used to support risk analysis, and LCA for environmental impact calculation. Some concepts integrating the environmental aspects with risk analysis have been identified in literature: the Environmental Effects Analysis (EEA), the Environmental Failure Modes and Effects Analysis (E-FMEA), the Environmental Failure Modes, Effects, and Criticality Analysis (E-FMECA), and the Circularity Impact and Failure Analysis (CIFA) approach, which allow the integration of obsolescence and recyclability considerations in the FMEA.

EEA is a qualitative method for Design for Environment (DfE) designed to be used in the early stages of product development, and is an approach that considers the economic and technical aspects. The objectives of an EEA are to point out and evaluate noteworthy environmental impacts of a product in the early phase of a development project. This is for the purpose of being able to evaluate alternative solutions (materials, processes, etc.) as early as possible. Subsequently, the harmful environmental impact of the product's life cycle may be limited or even effectively prevented [33]. The EEA framework emphasizes that EEA data gathering should include all phases of the life cycle (Purchase/Procurement – Production – Use – End of Life Treatment), but not necessarily in detail. The result of the EEA is to identify several considerable environmental impacts caused by the product. Consequently, several corrective and preventive actions are to be suggested. When the suggested actions are realized, a follow-up analysis is made through the re-evaluation of the environmental impacts in order to check for the effectiveness of the actions. The EEA would be performed according to the principal methodology in figure 9. It was underlined by

Lindahl [33] that the feedback arrows should not be interpreted too literally since EEA is an iterative process and in reality, there is always feedback. On the other side, Roszak et al. [34] highlighted that E-FMEA is one of the eco-design tools used in the product design process which takes into account the environmental impacts caused by technical problems, deficiencies, irregularity errors or processes. Values ranging from 1 (small risk) to 10 (high risk) are assigned to the three criteria (i) importance of environmental impact (S), (ii) the probability of cause occurrence (O), and (iii) the causes of influence (D).

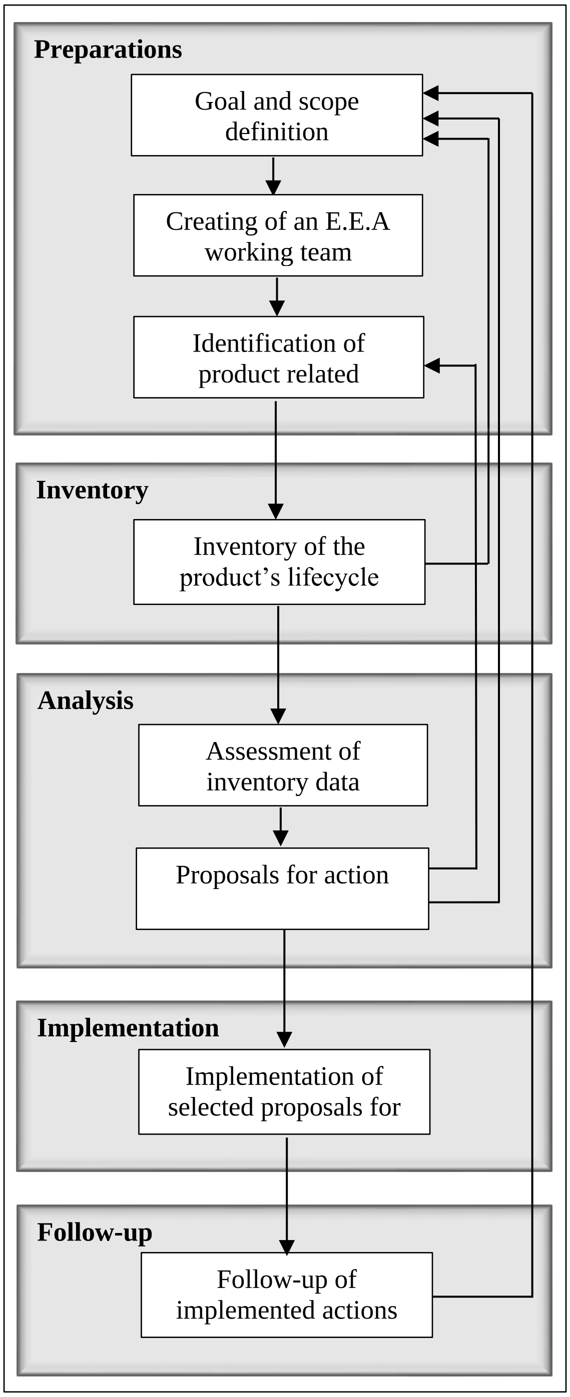

Fig. 9. EEA methodology flow chart (Reproduced from [33])

The Risk Priority Number (RPN), so-called Criticality, is obtained by multiplying S per O per D. General criteria used in the particular parts of the proposed E-FMEA analysis focused on several directions to adopt the indicators:

- O indicator: possible risks for the hazards of the process impact on the environment, encompassing the exceeding of standards and scopes, the established law for the process, machine failures, and technological equipment used during the process – which influences the environment.

- S indicator: The gravity of the impact of the equipment and machinery failure on the environment, outstripped environmental standards and ranges of the process, and the continuity of the process.
- D indicator: The detection of equipment and machinery failure influencing the environment, as well as outstripping standards and environmental ranges in the process.

Lindahl [35] discussed the importance of environmental demands in the early design product process, and the need for an efficient DfE-tool for small and medium enterprises and then introduced the E-FMEA tool as a new promising tool for an efficient Design for the Environment. Figure 10 provides some needed inputs to accomplish an E-FMEA, which will be sorted according to the life-cycle phases of the product, reformulated, and analy The next step is reserved to evaluate which environmental aspects and impacts should be regarded as significant. Therefore, the designer proceeds to rate while considering three different criteria: S for controlling documents, I for public image, and A for environmental consequences. These criteria are evaluated from 1 to 3, depending on compliance from an environmental perspective. The Environmental Priority Number (EPN) is then calculated by summing the three numbers S, I, and A. A fourth criterion, called F, is introduced to account for the improvement possibility, which spotlights the effort in time, cost, and technical possibility needed to environmentally enhance a product or a component of a product. Improvement possibility is rated from 1 (no possibility for improvement) to 9 (very good possibility for improvement). The final step is to recommend actions depending on the EPN and improvement possibility.

Bertoni [36] integrated circularity considerations regarding product development, early in the design process, using FMEA and FMEA Boundary Diagrams. He presented the first results of an approach named Circularity Impact and Failure Analysis (CIFA) limited to the integration of obsolescence and recyclability considerations in the FMEA. The first step of the CIFA analysis consists of a checklist to establish the potential recyclability of the system on five key dimensions: disassembly method of the system, material compatibility of components, type of material used in the systems (based on the material group) and contamination of product components to be considered in the end-of-life. This first step is followed by the identification of the probable causes of failure and the relative assessment of the probability of occurrence and severity. A score from 1 to 4 is allocated from the less risky to the more problematic recyclability condition. A final Recyclability Impact Risk is determined by multiplying the probability and severity with the recyclability risk for each of the 5 recyclability dimensions, with the purpose of guiding the prioritization of the actions to be engaged to prevent failures. zed. Some examples of the E-FMEA results under the form of recommended actions are shown in Figure 11.

The E-FMEA procedure proposed by Lindahl [35] relies on five steps using an E-FMEA form (Fig.11). The first step is to point out the products/process life-cycle stages, besides identifying all activities related to each stage. The second step is to find environmental aspects (emissions to the atmosphere, waste, contamination of land, etc.). In the following step, the designer has to identify, for each environmental aspect, the caused environmental impact (ozone depletion, greenhouse effect, etc.).

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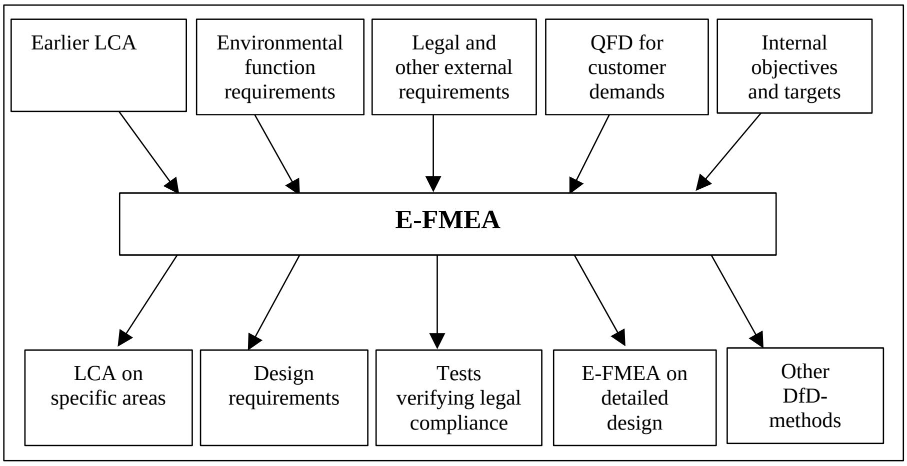

Fig. 10. The E-FMEA Input and Output (Reproduced from [35])

ENVIRONMENTAL FMEA DESIGN															
Customer			**Part name**	**Dwg No.**					**Supplier**						
			Spark												
Function			**Date**	**Issued by**					**Project**		**Issue**				
washing machine			1996-08-09	Carsten Jensen					PW111						
ENVIRONMENTAL CHARACTERISTICS					**RATING**				**ACTION-STATUS**						
No	**Life cycle phase**	**Activity**	**Environmental aspect**	**Environmental impact**	**S**	**I**	**A**	**EPN/F**	**Recommendations**	**Decisions taken**	**S**	**I**	**A**	**EPN/F**	**Dept/ Sign**
	Production	Welding of 25 different pieces	Emissions to air from welding the drum	Toxical	2	1	3	6/5	Single-shot polypropylene molding the drum						
		Cleaning and painting the cabinet	Emissions to atmosphere from VOC	Toxical and ozone depletion	2	1	2	5/3	Look into the possibility for prepainted cabinet						
		Working on components for the drum	Metal waste from working 30 different components	Resource consumption material	1	1	1	3/7							
	Use	Washing and rinsing	Use of resources water	Resource consumption water	1	2	1	4/5							
		Use of detergents	Release to water (waste water)	Eutrophication	1	2	1	4/3							
		Pumping and heating the water, spinning the drum	Use of resources electricity (1,5 KWh)	Resource consumption energy 50% nuclear power	2	2	2	6/4	Develop electronic control system to regulate energy use						
	Disposal	Disassembly of polymer components	Use of materials polymer (not marked)	Resource depletion	2	1	1	4/4							
			Emission to the atmosphere from flame retardants	Ozone depletion	3	2	2	7/5	Does the plastic material contain brominated subst?						
		Disassembly of electronic components	Contamination of land from toxic materials e.g., cadmium etc	Toxical	3	2	2	7/8	Do the plastic components contain toxic materials?						

Fig. 11. The E-FMEA form (Reproduced from [35])

3. DISCUSSION AND PROPOSAL

AM sustainability studies are under development and are multiplying more and more. The most used tool is the LCA tool. The life cycle analysis includes an impact assessment phase, which takes a long time to be carried out and requires a lot of information, which could not easily be accessible. Especially if the analysis is not cradle-to-cradle limited but targets a cradle-to-gate product life cycle. In order to consider the entire life cycle without overloading the analysis and delaying the design process, we opt to take into account an iterative LCI approach rather than an LCA, especially since we consider the conceptual phase. Actually, in this conceptual phase, the CAD is not yet done but we must be aware of the constraints and the opportunities it offers in terms of DfAM tools; that we have already presented in section 3. The techniques of Design for X with their two categories (design for efficiency and green design) are being applied in the different design phases [37]. Specifically, the Design for AM must be used; using the DfAM rules and guidelines which are fundamental data that will allow the designer to act in a preventive way.

The literature review given in the previous section brings together the available tools integrating the environmental aspect into the risk analysis that the authors have consulted. To the author's knowledge, no use of these eco-design tools has been made in an AM environment in terms of AM technics constraints and opportunities. To fill in this gap, while taking into account the conclusion of Lindahl [35], which states that, in general, E-FMEA is a useful tool/method in the early design stages of all kinds of product development processes, we propose an approach that integrates the DfAM into FMECA tool with an LCI vision.

3.1. Extended FMEA Approach

The application of the Failure Modes, Effects, and Criticality Analysis method has been an established practice in systems engineering and engineering design for some decades. The profit of applying FMECA is to increase engineers' awareness of potential hazards related to a specific design configuration, in such a way that the corrective actions can be preventively arranged to avoid probable failure to occur.

The FMECA is a tool usually used for quality improvement and risk assessment. We propose to consider the reduction of the environmental impact of a product as a quality objective. Consequently, FMECA could contribute to the achievement of this purpose. The FMECA could be used as a semi-qualitative assessment tool whether under eco-designing a new product or eco-friendly improving an existing one. Account for the environmental impacts in an FMECA analysis through a systematic listing of potential environmental hazards associated with a product or process, before their consequences appear, gave rise to the Environmental-Failure Modes Effects and Criticality Analysis (E-FMECA).

Furthermore, to be more efficient, we suggest integrating the E-FMECA tool in the early design stage. Considering the three components of sustainable development (social, environmental, and economic dimensions) when analysing the different phases of the life cycle, the analysis is so-called Sustainability - Failure Mode, Effects, and Criticality Analysis (S-FMECA). The application to the specific case of designing for additive manufacturing is the aim of the present proposal.

We consider that the spirit of sustainability is a life cycle approach. Hence, the proposed spreadsheet in figure 12, to use in the early design stage to analyse the entire life cycle of the product, would present in its first column the different LCA stages: raw material extraction, manufacturing, distribution, usage, and end of life. To emphasize the importance of the design phase, a separate stage has been reserved for it.

The different sources contributing to AM sustainability as identified by Khalid & Peng [25] in their three dimensions (see figure 4) are taken up as a failure mode according to the stage of nature. Other failure modes can enrich the list since, at this phase of the analysis, we are looking for any possible and probable failure. Afterwards, the failure mode effects and causes have to be identified. If any existing sustainability indicator exists, it should be specified in the seventh column of the S-FMECA form.

Traditionally, in FMEA, the evaluation index (C) is the metric of the criticality and risk assessment, which is also called the risk priority number (RPN). Criticality (C) is dependent on three criteria (Table 2): the degree of severity (S), the occurrence probability (O), and the detection (D). Where the severity characterizes what is the relative severity of the failure mode effects, the occurrence characterizes what is the relative probability of occurrence of the failure mode causes and the detection characterizes what is the degree of availability and ease of access of the environmental indicator. Consequently, criticality is calculated by multiplying the three scores of the three criteria.

$$C = S * O * D \tag{1}$$

The proposed rating scale of (O), (S), and (D) indexes for environmental risk in S-FMECA analysis would be defined as explained in Tables 3, 4, and 5. The severity degree (S) would be chosen according to the value of the sustainability indicator if any were existing. If it would be impossible to find or to define an indicator, qualitative appraisement and estimation would be made. The Occurrence degree (O) would be estimated according to the probability of the manifestation of the failure mode. The Detection degree (D) would be attributed depending on the availability of the sustainability indicator information on the early design stage and the ease of access to this indicator.

The case where a given failure mode is very likely to appear and whose effect is very serious but the designer does not have any information about it (no indicator) and it is expected that this information will never be available in the short term, will be assigned S = 5, D = 5 and O = 5 scores. Then, the criticality will be at its maximum value.

In the column *Recommended Actions* in the S-FMECA form (Appendix), preventive and corrective actions will be recorded. The prioritization of the interventions will depend on the criticality score. The more critical the failure mode, the more priority the intervention will have. Once an action is applied, a re-evaluation of the scores is made and a new order is established.

Thus, the proposed tool has the advantage of being adaptive to the evolutions of the whole process progression. The S-FMECA tool in a digital spreadsheet form will be updated as the processes progress. To illustrate the method, some examples of recommended actions, according to the failure mode cause, are given in the Appendix. The proposed S-FMECA analysis uses the assessment of the 4 important criteria to be met by the AM production process:

- Meeting the design for AM guidelines;
- Meeting the economic requirements in the field of sustainability development;
- Meeting the social requirements in the field of sustainability development;
- Meeting the environmental requirements in the field of sustainability development.

Society LOGO	**Sustainability - Failure Mode, Effects and Criticality Analysis**									REFERENCE Revision: Edition date: Date of update:						
Product/System:	**Workgroup:**									**Page:**						
Process / Stage	**Failure Modes**	**Failure Effects**	**Severity**	**Potential Causes**	**Occurrence**	**Sustainability Indicator/ Measurement**	**Detection**	**Criticality**	**Recommended actions**	**Responsible / deadlines**	**Type ***	**S.D. ****	**Evaluation** G	F	D	C
Design																
Raw Materials																
Production																
Assembly																
Distribution																
Consumption Use																
End of Life (EoL)																
Sustainability Dimension **	⊕ Environmental				⊕ Economical		⊕ Social									

Fig. 12. The proposed S-FMECA form

Table 2. Criteria definition

Severity	**Occurrence / Frequency**	**Detection**	**Criticality**
What is the relative severity of the failure mode effects?	What is the relative probability of occurrence of the failure mode causes?	What is the degree of availability and ease of access of the environmental indicator?	What is the priority of the listed failure mode?

Table 3. Rating scale of the criterion Occurrence (O)

Failure mode Frequency	**Definition**	**Index**
Very high - Inevitable	The probability of occurrence is very high. The failure mode appearance is inevitable.	5
High - Frequent	The probability of occurrence is high. Frequent failure mode	4
Moderate - Occasional	The probability of occurrence is moderate. Occasional failure mode.	3
Low - Infrequent and spaced	The probability of occurrence is low. Infrequent and spaced failure mode.	2
Very low - Improbable	The probability of occurrence is very low. Unlikely and improbable failure mode.	1

Table 4. Rating scale of the criterion Severity (S)

Severity	**Effect of failure mode**	**Index**
Very serious	Failure mode effects involve very high sustainability indicator values (costs, time, energy consumption, health and safety, non-compliance with a standard, law, or regulation, etc.), or qualitative estimation.	5
High	Failure mode effects involve high sustainability indicator values (costs, time, energy consumption, need to sort out some of your products and services to reject	4

Severity	Effect of failure mode	Index
	those rendered unusable, or of inferior quality that cannot be repaired, health and safety, etc.), or qualitative estimation.	
Moderate	Failure mode effects involve moderate sustainability indicator values (costs, time, energy consumption, health, and safety, need the rejection of a portion of your products and services rendered unusable without sorting, etc.), or qualitative estimation.	3
Low	Failure mode effects involve low sustainability indicator values (costs, time, energy consumption, health, and safety, requiring taking back or repairing part of your products and services, etc.), or qualitative estimation.	2
Very Low / Nothing	No effect or failure mode effects involving very low sustainability indicator value (costs, time, energy consumption, health, safety, etc.), or qualitative estimation.	1

Table 5. Rating scale of the criterion Detection (D)

Failure mode	Definition	Index
Very difficult	No sustainability indicator. Failure mode Impossible to control, measure, or assess.	5
Difficult	The sustainability indicator is not available in the Early Design Stage but could be recovered in the later stages of the design.	4
Moderate difficulty	Quantitative sustainability indicator is not available in the Early Design Stage, but the failure mode can be accessed via a qualitative indicator. Sustainability indicator inspired from other similar cases. Not 100% suitable but could indirectly give an assessment. Only a part of the environmental indicator data is available.	3
Easy	Quantitative sustainability indicators are available in the Early Design Stage. Quantitative indicators require significant investigation and measures to obtain them.	2
Very easy	Quantitative sustainability indicators were available in the Early Design Stage. Easy to access. Specific to the studied case.	1

3.2. Sustainability Indicators

In the circular economy context, Kristensen & Mosgaard [38] reviewed 30 micro levels, i.e. product level, circular economy, product level, and indicators dedicated to measure CE at the level of the product or the single firm. It was then noticed that most indicators focused on recycling, remanufacturing, or end-of-life management, whereas fewer indicators scrutinized disassembly, waste management, lifetime extension, reuse, or resource efficiency.

Considering the three dimensions of sustainability, it was underlined that the majority of indicators consider closely economic aspects, with environmental and particularly social aspects included to a reduced extent. The reviewed indicators are scattered between single analytical guidelines or tools, quantitative indicators, and composite indicator set, indicating a diverse method to measuring CE. After collection, census, and categorization, Kristensen & Mosgaard [38] concluded that the majority of micro-level indicators are developed to evaluate individual materials and products, and consequently function to support decision-making processes. The more complex the indicator is to be calculated, the more challenging it will be to use in practice, as the resources require to obtain and organize as it can be excessive. Consequently, in the present proposal, we chose to associate a score according to the availability of the indicators, especially since certain indicators can only be calculated at an advanced stage of the design or even in the phases after the design. The graph given by Khalid & Peng, [25] in figure 4 gives us ranges in variation regarding the value of the specific energy consumption (SEC) of different AM techniques. We consider that the SEC could be used as a sustainability indicator and propose to attribute a Sustainability Coefficient (SC_E) according to the maximum SEC for each AM technique (Table 6). Thus, an index from 1 to 6 is assigned such as: for a maximum SEC_{max} inferior to 250 MJ/kg, the index 1 is attributed; for a maximum SEC_{max} between 250 and 500 MJ/kg, the index 2 is attributed; and so on with an interval of 250 MJ/kg up to 1000. If SEC_{max} is superior to 1000 MJ/kg, the index 5 is attributed.

Likewise, the cost per part can be considered as a sustainability indicator and a Sustainability Coefficient (SCc) would be affected (Table 7). Thus, an index from 1 to 5 is assigned such as: for a cost per part inferior to 200$, the index 1 is attributed; for a cost per part between 200 and 350$, the index 2 is attributed; for a cost per part between 350 and 450$, the index 3 is attributed and for a cost per part between 450 and 550$, the index 4 is attributed. If the cost per part is superior to 550$, the index 5 is attributed.

Table 6. Specific Energy Consumption Sustainability Coefficient (SC_E)

AM technique	SEC range (MJ/kg)	SC_E
SLA	75-148	1
DMLS	241-339	2
LENS	86.4	1
SLM	83-588	3
SLS	36-4849	5
EBM	59-177	2
FDM	2-1246	5

Table 7. Cost per part Sustainability Coefficient (SC_C)

AM machine	AM technique	Cost per part ($)	SCc
3D Systems DMP320	SLS	343,77	2
3D Systems DMP500	SLS	576,87	5
EOSINT M290	DMLS	317,14	2
EOSINT M400	DMLS	525,81	4
GE Arcam A2X	EBM	779,63	5
Renishaw AM250	SLM	220,26	2
Renishaw AM500	SLM	516,93	4
SLM Sol. SLM280	SLM	277,33	2
SLM Sol. SLM500	SLM	540,25	4
Aconity One	LPBF	490,62	4
DMG Mori 30 SLM	DMLS	313,87	2

In figure 8 [30], it was shown that toxicity is, inter alia, size-dependent, and surface-area-dependent. The authors noticed a minimum in the deposition fraction for the particle sizes between 0.1 and 1µm. It may be possible to recommend the use of particles of a size within this range to minimize the toxic effect of the particles for AM powders.

This recommendation remains subordinate to the technical validity. Thus, we suggest considering the powder size as a sustainability indicator for safety and health and a Sustainability Coefficient (SC_H) would be attributed (Table 8).

Table 8. Health Sustainability Coefficient (SC_H)

Metal Powder size	SC_H
Inferior to 0.1 µm	5
Between 0.1 and 1µm	1
Superior to 1 µm	5

4. CONCLUSIONS

The choices made at the design stage will largely define the environmental impacts of a product. Particularly, additive manufacturing - related information used for assessing quantitatively the sustainability of a product is frequently unavailable in the early design stage (EDS). Instead of that, the designers rely on qualitative estimations to make decisions. Semi-qualitative methods seem to be a good compromise at this EDS. This article presents a semi-qualitative eco-design method, suitable for the early design stage, that relies on the Failure Mode, Effect, and Criticality Analysis (FMECA) with a Life Cycle Inventory (LCI) vision and consideration of additive manufacturing constraints and opportunities. Based on the reviewed literature and the proposed approach, the following conclusions can be drawn:

- It is important to consider an analysis of the entire life cycle during a sustainability study. A Life Cycle Inventory approach would be better suited to the early design stage than a Life Cycle Analysis but if LCA data are available in EDS, it should be properly operated. The proposed rating scale of the criterion Detection in our S-FMECA tool allows considering the data availability through the different design stages.
- It is crucial to include the Design for Additive Manufacturing (DfAM) guidelines and rules into eco-design tools. In particular, our proposed S-FMECA tool, which is developed based on a risk analysis approach, allows the designer to be aware of the DfAM failures caused since the early design stages, to act preventively.
- The three-bottom line dimensions of sustainability should be considered. The proposed S-FMECA method foresees recommending improvement actions considering the three sustainability pillars: social, economic and environmental.

The proposed tool has the benefit of being adaptive to the evolutions of the whole process progression from the conceptual stage to the embodiment one to the final detailed design stage. The S-FMECA tool is a digital spreadsheet form that will be updated as the design process progresses. The main advantage of the proposed tool is that it makes it possible to overcome the lack of information or the little information available at the early design stages but as the process progresses and the information becomes accessible, adaptation is quickly initiated and according to the re-evaluation of the criticality, a new prioritization of actions is made.

However, despite the advantages of the method, the S-FMECA tool applicability needs to be investigated in industrial case studies, whether in functional or aesthetic parts. Moreover, the proposed tool currently takes the form of an Excel© spreadsheet. It would be more judicious to develop a platform that could allow communication with other software. Mainly in the advanced design phase where computer-aided design, computer-aided manufacturing, life cycle assessment, and product life cycle management software are used.

Future research will focus on (i) implementing the S-FMECA tool at a partner company and (ii) developing an S-FMECA based collaborative tool to provide the designer instructions about sustainability when designing for additive manufacturing.

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APPENDIX

Examples of recommended actions according to the failure mode cause

Process / Stage	Failure Modes	Failure Effects	Potential Causes	SI	Recommended Actions
Design	Heavy product weight	Increased energy and CO_2 emissions in both AM manufacturing and using phases	Design for lightweight products not performed		Topology optimization
			Wrong selection of material		Selection of a low-density material [39]
			DFAM not applied		Lattice generation
	Low Profitability	Economic loss-market loss	High designed product cost		Use standard part: If someone already makes the part you want, it will almost surely be cheaper to buy it than to fabricate it [39]
		High product cost	Material selection		Use the fewest of materials as possible: it reduces inventory costs and the range of tooling the manufacturer requires, and it can help with recycling [39]
		High Lead time	Assembly takes time		Make the parts easy to assemble (Design for Assembly: minimize part count, design parts to be self-aligning on assembly, use joining methods if needed that are fast) [39]
					Part consolidation (DfAM)
		Productivity	Long unit manufacturing time		Temporal design for additive manufacturing [40]
			Number of parts		Batch size: multiple parts within one AM machine vat or chamber as many as possible (limited by the dimensions of the AM machine) / verify if economic batch size is reached /apply ‘Grouping parts’ methodology [5], [39]
	Customer satisfaction	Economic loss-market loss	Bad identification of technical requirements		Do not specify more performance than is needed [39]
	Designer empowerment	High working time and poor design quality	Unmotivated employee/ irresponsible/ incompetent/ not autonomous		Management Support/Focus On The Customer/ Front line Decision Making/ Ongoing Training/ Access To Data/Managers Trust Employees/ Boundaries Are Clearly Defined/ Employees Have Mentors/ Employees Receive Positive Reinforcement/ Align Compensation With Customer Needs/ Consider Social Style/ Give Employees The Tools They Need/ Plan For Empowerment [41]
	Machine /AM technique selection	Additive manufacturing time too long	100% AM strategy		Consider the hybrid machine alternative
		Air pollution causing an increase in the greenhouse effect which causes global warming	High Energy consumption	SC_E	Select the convenient AM machine that has a minimum SEC
		High manufacturing cost	High cost per part	SC_C	Minimum cost per part ($) among eligible machines
	Material selection	High material costs	Custom-made composition material is expensive		Seek the use of standard materials [39]
			Performance speciation more than needed		Do not over-specify the needed material performance [39]
		Health and safety: Parkinson's, Alzheimer disease; Asthma, bronchitis, cancer, etc.	Metal Powder size	SC_H	If possible, utilize particle sizes between 0.1 and 1 µm