S-FMECA BASED COLLABORATIVE DESIGN PROPOSAL FOR ADDITIVE MANUFACTURING METHODOLOGY

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ABSTRACT

In the current context, the sustainable development, eco-design and eco-manufacturing concepts are being developed in research laboratories, and further being integrated gradually into manufacturing industries. Hence, the needed information for eco-design is scattered throughout the product life cycle and is not centralized; especially when designing for Additive Manufacturing. This paper aims to develop a collaborative eco-design methodology by using eco-design tools in different design stages and, finally, to contribute to tackling this issue. Either in the early design stage or in the detailed on, the designer will be supported to make sustainable, conscious decisions. The proposed methodology based on the sustainable-failure modes, effects, and criticality analysis (S-FMECA) eco-designing tool allows the communication with computer-aided design (CAD), computer-aided manufacturing (CAM), life cycle assessment (LCA), topology optimization (TO) and product life cycle management (PLM) software in order to assist the designer to make green-conscious decisions.

KEYWORDS: eco-design methodology, S-FMECA, topology optimization, collaborative design, sustainability

1. INTRODUCTION

The burgeoning field of additive manufacturing (AM) is revolutionizing the production landscape. AM techniques are presumed to be green processes [1]. Their potential to create complex and customized product shapes while reducing weight [2] and material consumption [3], are the main reasons for this statement. The concepts of eco-design and eco-manufacturing arise to enhance the application of the circular economy. By aiming for sustainable development and considering the respect of the environment, manufacturing a product implies not only delivering at the right time and at an optimized cost in the required specifications (the right shape, the exact dimensions, the minimal roughness, and the specified material properties), but also to minimize environmental impacts by eco-designing and eco-manufacturing. Reducing the environmental impact of a product during its whole life cycle is a challenging issue for designers nowadays. Especially since the designer needs to take advantage of the opportunities provided by AM in terms of Design for Additive Manufacturing (DfAM) rules, guidelines, and tools [4]. For example, topology optimization software is an essential tool for product lightweight [5].

Indeed, the product development process considered as a collaborative process needs, classically, the integration of several expertise, such as manufacturing, quality, mechanical optimization, and recently, the environmental aspects [6]. Connecting eco-design software tools with traditional design tools, such as CAD, CAM, and PLM systems, therefore need to be studied in detail, in addition to the integration of TO software. In particular, while designing for AM. Therefore, eco-designing for additive manufacturing using the range of computer-aided design tools, while taking into account the challenges across the entire product lifecycle, is a tough issue. From Customer Voice Analysis (CVA) and Early Design Stage (EDS) to the Detailed Design Stage (DDS) and sustainable product production, the made choices are determinants of the final product's environmental impact [7]. In an eco-design process, the environmental sustainability concept is incorporated into each phase of the design process [8]: from design generation in the EDS to the DDS. In the early design stage, different design options are ideated and assessed based on the design

https://doi.org/10.35219/awet.2023.04
Date of submission/acceptance: 09.11.2023/22.12.2023

requirements. While in the last one, the optimal design is selected based on different analysis validation, especially computer-aided analysis, such as using Computer-Aided Engineering (CAE) or Finite Element Analysis (FEA) software. However, integrated eco-designing for additive manufacturing methodologies is still in the first steps.

Contributing to tackling this issue, this paper aims to develop a collaborative eco-design methodology for AM by using eco-design tools in different design stages. Regardless of the design stage, the designer will be supported to make sustainable conscious decisions. The proposed methodology based on the sustainable-failure modes, effects, and criticality analysis (S-FMECA) eco-designing tool, would allow the communication with computer-aided design software, computer-aided manufacturing software, life cycle assessment software, product life cycle management software, and topology optimization software in order to assist the designer to make green-conscious decisions.

The paper is organized in such a way that we start with a literature review encompassing the eco-design concept, DfAM concept, eco-design for the AM tools, and methodologies to lead to the identification of the research gap. The section 3 is dedicated to a proposal of an integrated eco-design for the AM methodology. Section 4 contains a discussion of results. Finally, conclusions and future research directions are provided in Section 5.

2. LITERATURE REVIEW

Although Industry 4.0 was assumed to promote sustainable development, it has ignored or misunderstood many fundamental sustainability concerns, which steered to the emergence of the Industry 5.0 paradigm. Sharma et al. [9] conceptualize Industry 5.0 as a revolutionary and disruptive innovation that reforms the manufacturing paradigm, propelling a transition from a linear economic model to a circular economy. In this context, Ghobakhloo et al. [10] developed a strategy roadmap for enabling Industry 5.0 transformation and concluded that eco-innovation and sustainable value network reformation, which entails developing digital supply networks that are modular and adaptive, are among the most complex and hard-to-develop enablers. Thus, digital integration and collaboration in Industry 5.0 transformation are essentially allowing the move from linear designs into more circular and dynamic ones. In this context, several scholars investigated the collaboration between eco-design software and CAD, CAM, LCA and PLM systems.

2.1. Eco-Design Integrated Concept

In her thesis, Poulikidou [11] assessed design strategies for improved life cycle environmental performance of vehicles and managed to identify a rich toolbox of 41 qualitative and quantitative design for environment (DfE) tools that need different levels of complexity and data demands. While discussing the integration of engineering design tools, Poulikidou pointed out the limited number of the identified DfE tools that offer possibilities for tool integration.

Several researchers have already explored the connection between CAD and eco-design software. For example, Mathieux et al. [6] developed a research work aiming to connect CAD software and PLM systems with eco-design software tools, mainly LCA software.

Gaha et al. introduced an eco-design methodology based on eco-features [12], [13]. It consists of calculating the environmental impact of an artifact till the detailed design phase. The proposed features-based model enables to integration CAD, CAM, Computer Aided Process Planning for Manufacturers (CAPP), PLM, and LCA systems. This eco-designing methodology is an algorithm that allows designers to appreciate the environmental impact of each feature selected in real-time and allows them to choose the optimal sustainable scenario.

Tao et al. [14] and Chen et al. [15] succeeded in a CAD-LCA software integration based on eco-feature technology. Tao et al. [16] have also developed an integrated eco-design optimization model using Dassault Systèmes Isight tool.

2.2. AM Concept Design

The state-of-the-art [17] of DfAM guidelines, rules, best practices, and tools show numerous and versatile knowledge that a designer for AM needs to become accustomed to in the different design process phases. The designer needs to be aware not only of the AM opportunities but also of the AM design restrictions. The EDS is crucial [18] as the earlier the designers satisfy the DfAM rules and guidelines and use the DfAM tools, the more efficient the design will be.

For instance, if the designer is not mindful about the DfAM guideline stipulating "Minimize the strength of the connection between the support structure (frequently needed to support overhangs e.g.) and the final part", he could strengthen too much the support, so it will become difficult to remove it and even could alter the surface quality. The support structure could even induce strains and stresses; consequently, the designer would need to conduct thermal simulation modelling for validation. Therefore, acting preventively to guarantee a certain surface quality of the final product, for example, could be planned since the design process.

At the early design stage, intuitive tools like DfAM Booth Worksheet [19] and LiDS Wheel [1] could be used. Nevertheless, in the DDS phase, more sophisticated tools could be utilized. Usual CAD design software (SolidWorks©, CATIA©, Creo©, etc.) are then used in symbiosis with new AM dedicated software (nTopology©, Simufact©, Creo GTO©, Siemens NX©, Cura©, Simplify3D©, etc.) in order to optimize the topology [20], generate lattice, create the support structure and simulate the AM process. This is to allow lightweight and robust designs [21]. Which leads to lower energy consumption and therefore, more sustainable products. In a previous work [17], we proposed a DfAM framework (figure 1) to act preventively and minimize iteration loops during designing for additive manufacturing.

2.3. Eco-Design for AM Tools and Methodologies

LCA is the most renowned methodology to carry out environmental assessments of products as well as services [22]. Since LCA can only be effectuated at the later stage of the design process, Yi et al. [7] suggest using energy performance assessment to replace LCA in eco-design for AM to intervene in the early design stages. Their proposed approach uses a three-part holistic framework: a simulation tool for prediction of the AM energy consumption using the G-code as an input, an assessment model for the AM energy performance, and general workflows of eco-design for AM.

Mami et al. proposed a framework for eco-design for additive manufacturing by modifying LCA and life cycle cost analysis [23]. In their eco-efficiency methodology, the environmental impact and cost are quantified, analyzed, and decreased in the design for the AM stage. Upon completion of their study, they concluded that 3D printing provides significant sustainability improvements over conventional machining in aeronautics even if the optimal scenario still relies on the chosen trade-off between environmental impacts and cost reduction due to 3D printing equipment's high costs. Yang et al. proposed a method to use LCA to evaluate the environmental impacts of the production, and after that use the part consolidation technique supported by AM to decrease the environmental impacts [24]. Likewise, Burkhart and Aurich proposed an LCA-based framework to diminish the environmental impacts in commercial vehicle production [25]. The study conducted by Liu et al. [26] aimed to develop a DfAM framework to provide guidance for designing end-use consumer products using plastic AM processes. Their proposed framework is built upon contemporary design practices adopted by AM practitioners and professional designers.

2.4. Research Gap

It appears from the literature review that each design stage has its own DfAM tools. This leads us to the following research question: *Would it be possible to capitalize on the information from the start of the design process and develop an eco-design tool that can be used either in EDS or DDS?*

Indeed, from the moment we arrive at the integration phase between CAD and CAM software with LCA software, the designer is already in the detailed design phase while a majority of the sustainability characteristics of a product are attributed during the early design stage [1]. Unfortunately, eco-design tools in the preliminary design phase remain limited to guidance tools such as:

- Guidelines for product development and product design.
- Checklist: This tool gives answers to the question: where is the main environmental problem? First, a set of sustainability criteria are listed. Next, each criterion is graded according to a compatibility scale or a five-point scale for example [27]. At last, the designer has to interpret the result.
- Performance indicators (product planning, development, and design): Material Input Per Unit Service (MIPS) and Material Intensity (MIT) are indicators characterizing resources-consuming in the whole cycle of different materials, fuels, transport services, and food.

Such tools are suitable for the early planning and designing stages [28] while more detailed analytical tools can be successful in the detailed design stage due to data requirements, e.g., on specific product composition, processes involved, etc.

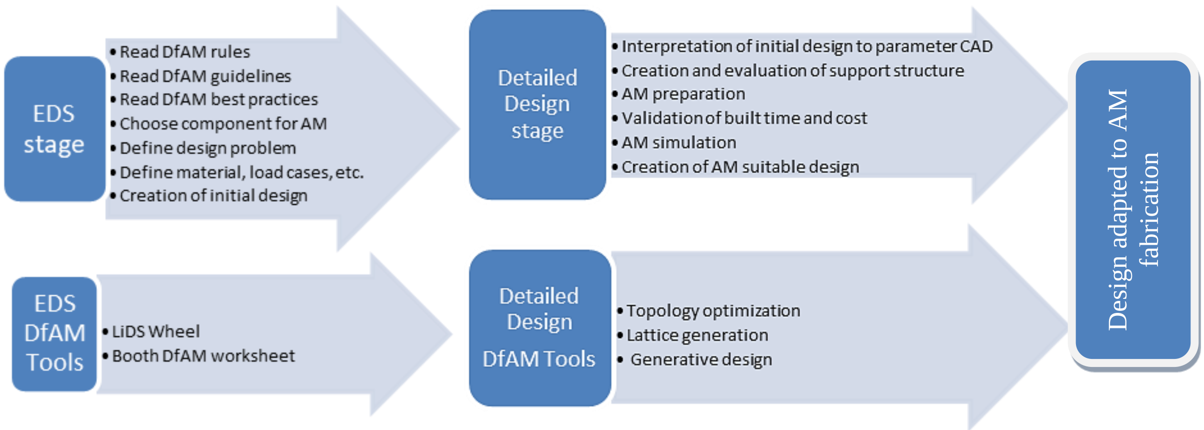


Fig. 1. Chtioui's proposed DfAM framework [17]

Early integration of the environmental aspects and the environmental performance product's assessment regarding the product development process is among the main objectives of the eco-design approach. A tool that could be integrated into all design stages would be advantageous.

Therefore, instead of only connecting existing design software tools, which are useful in a detailed design stage; some benefits might be reached when developing new methods and tools that could be integrated since the early design stage and still useful for later stages.

3. INTEGRATED ECO-DESIGN FOR THE AM METHODOLOGY PROPOSAL

Through information capitalization in the different design stages and inter-software collaboration, the authors aim to develop an inclusive methodology. Information from EDS, CAD, CAM, LCA, TO, and PLM/PDM (Product Life cycle Management / Product Data Management) are collectively gathered to design an artifact that transcends individual fields (materials science, design, manufacturing, etc.) and leads to a sustainable product from the cradle to the grave.

3.1. Identifying Relevant Design Tools

Lindhal [29] shows that current CAD solutions and geometric models are still considered today as the data reference by industry. Likewise, Mathieux et al. [6] reported that CAD, CAE, CAM, and PLM/PDM software tools are the most utilized tools in the industry. On the side of sustainability, Fontana et al. [22] reported that LCA is the most renowned methodology for carrying out environmental assessments of products as well as services.

Re-designing components for AM is the way to reach the goal of saving resources, either in used materials or in energy consumption [30]. Namely, the Topological Optimization (TO) has been applied in this context to lightweight components [31].

From the review study conducted by Spreafico [32], there appeared a growing interest in the methods related to the product functioning for supporting failure risks analysis in eco-assessment. The Failure Mode and Effects Analysis (FMEA) is a multi-criteria approach, largely used in manufacturing industries in different phases of the product life, inter alia in the design stage, as an effective and consistent risk assessment method in order to improve production and design [33].

Some methodologies integrating the environmental aspects with risk analysis have been identified in the literature:

- Environmental Effects Analysis (EEA) [34];
- Environmental Failure Modes and Effects Analysis (E-FMEA) [35];
- Circularity Impact and Failure Analysis (CIFA) approach [36].

Therefore, we propose to develop an FMEA -based methodology allowing the connection of CAD, CAE, CAM, PLM, and eco-design software. The proposed methodology would be integrated since the early design stage and still useful for later stages. A schematic diagram given in Figure 2 explains our objective of bringing together in a single eco-design approach the Life Cycle Inventory approach coupled with the DfAM rules and guidelines and the customer requirements in the first design stage. Creativity tools like Brainstorming or Six Thinking Hats could be used at this initial stage. The output of this phase is a first design solution, which requires optimizations. In the detailed design phase, the first form of the newly designed system/product will eventually need part consolidation, topological, optimization, and lattice generation to be appropriate for the AM techniques. Therefore, AM dedicated software like slicing and TO ones; would be used in addition to classical CAD and CAM software to generate the final system/product design. Integrating the LCA and PLM software will allow the eco-designing at this DDS.

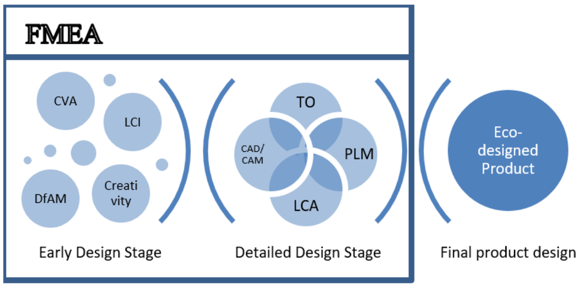


Fig. 2. Eco-design framework model

3.2. The Proposed FMEA-based DfAM Methodology

Since the preliminary design phase, a designer should act preventively and avoid any choice that could result in a significant environmental impact. We propose to consider design errors as well as bad choices as possible failures that it would be wise to avoid. Preventing failures from the early design stage would be possible by using the classic FMEA method while adapting it to take into account environmental aspects. A life cycle approach needs to be adopted since the conceptual design. Hence, the different LCI stages: raw material extraction, manufacturing, distribution, usage, and end of life; have to be considered.

An eco-design project is made of one or several products that we need to minimize its/their environmental impacts at each stage of its/their life cycle. Each stage (design, manufacturing, distribution, usage, and end of life) may contain several failure modes depending on the product to which it belongs. A failure mode can appear in several stages. In addition, each stage may have several failure modes. A failure mode can appear in several stages. For a failure mode, there could be one or more causes, effects, and sustainability indicators. There are three criteria and a critical factor for each failure mode. The critical factor is calculated by multiplying the three scores of the three criteria:

- severity of the failure (S) corresponding to the evaluation of the relative severity of the failure mode effects;
- occurrence (O) corresponding to the evaluation of the relative probability of occurrence of the failure mode causes;
- failure detection (D) corresponding to the evaluation of the degree of availability and ease of access of the environmental indicator.

Depending on the criticality value, a preventive action plan would be carried out. The proposed rating scale of (O), (S) and (D) indexes vary from 1 to 5 as mentioned in Table 1 and explained in Table 2. The eco-design for the AM methodology flow chart given in Figure 3 explains the procedural steps of the S-FMECA tool deployment in the EDS as well as in the DDS. In EDS, the process is divided into four different steps: the preliminary study, the inventory part, the evaluation stage, and the action phase. Afterwards, comes the detailed design phase where it will be necessary to communicate with the different used software in order to collect the required information for the environmental assessment.

Table 1. Rating scale

Very low / Nothing	**Low**	**Moderate**	**High**	**Very serious**
1	2	3	4	5

Once this information becomes available, the detection index needs to be updated according to table 2, and the criticality is re-evaluated. A new action plan needs to be performed accordingly. The implementation of this methodology would be easier to apply if a computerized platform could help the designer in his task. Therefore, a database is implemented for this purpose, and it will also work as a medium of documentation. A succinct description follows below.

Table 2. Rating scale of Severity (S), Occurrence (O), and Detection (D) criteria

Index	**Severity**	**Occurrence**	**Detection**
5	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.	The probability of occurrence is very high. The failure mode appearance is inevitable.	No sustainability indicator. Failure mode Impossible to control, measure, or assess.
4	Failure mode effects involve high sustainability indicator values (costs, time, energy consumption, need to sort out some of your products and services to reject those rendered unusable, or of inferior quality that cannot be repaired, health and safety, etc.) or qualitative estimation.	The probability of occurrence is high. Frequent failure mode.	Sustainability indicator is not available in the Early Stage Design but could be recovered in the later stages of the design
3	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.	The probability of occurrence is moderate. Occasional failure mode.	A quantitative sustainability indicator is not available in the Early Design Stage, but the failure mode can be assessed 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.
2	Failure mode effects involve a low sustainability indicator value (costs, time, energy consumption, health, and safety, require taking back or repair part of your products and services, etc.) or qualitative estimation.	The probability of occurrence is low. Infrequent and spaced failure mode.	Quantitative sustainability indicators are available in the Early Design Stage. Quantitative indicators require significant investigation and measures to obtain them.
1	No effect or failure mode effects involve very low sustainability indicator value (costs, time, energy consumption, health, and safety, etc.) or qualitative estimation.	The probability of occurrence is very low. Unlikely failure mode.	Quantitative sustainability indicators are available in the Early Design Stage. Easy to access. Specific to the studied case.

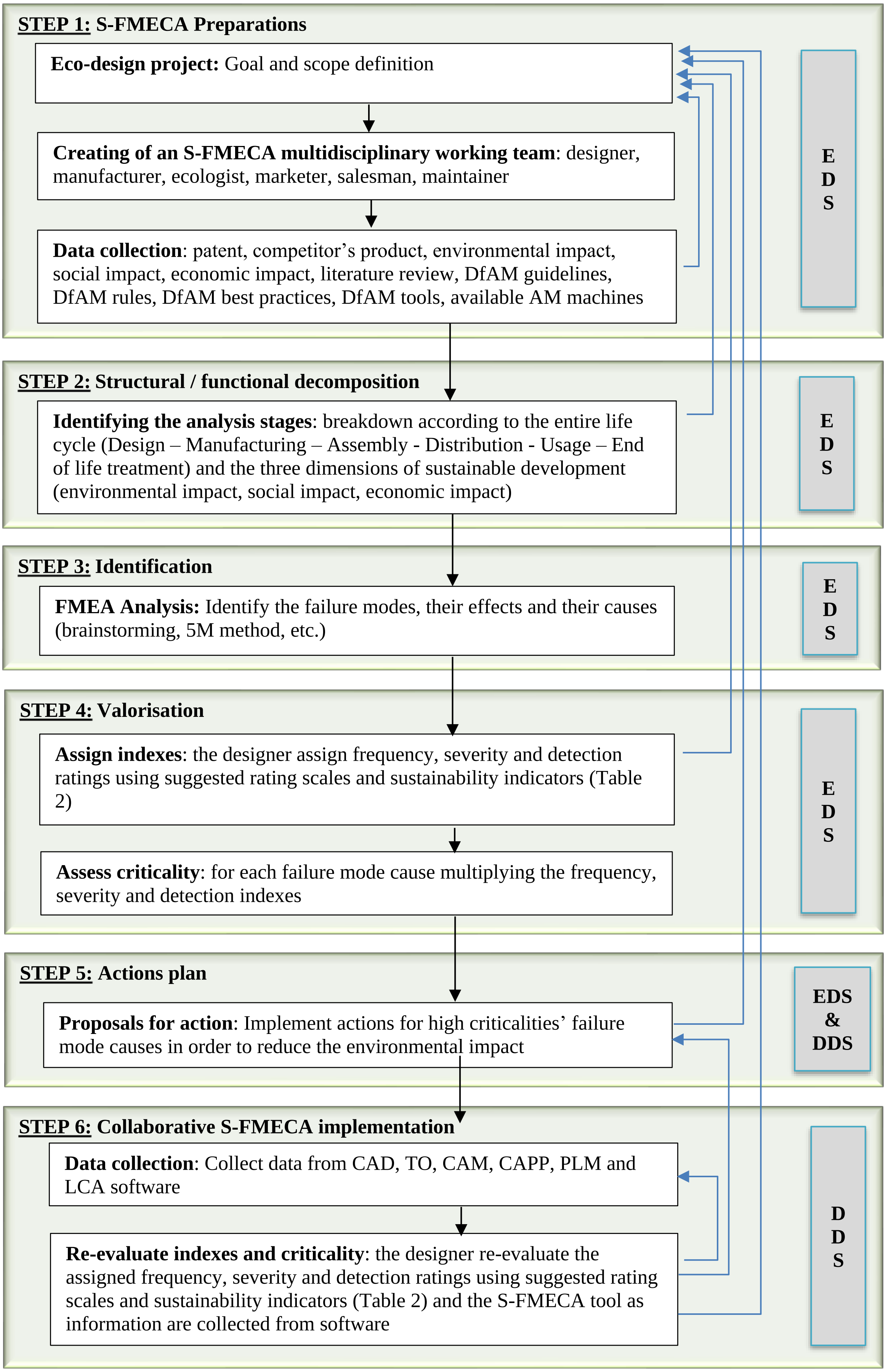


Fig. 3. The eco-design for AM methodology flow chart

3.3. S-FMECA Tool Implementation

A prototype of the proposed S-FMECA eco-design for the AM tool is developed using the Microsoft Access© software.

3.3.1. S-FMECA “Standard GUI interface”

The standard Graphical User Interface (GUI) has been designed to allow the user to define the eco-design project with his several products. For each product, the different stages regarding the entire life cycle stages cycle (Design - Manufacturing - Assembly - Distribution - Usage - End of life treatment) are analysed. For each stage, the whole possible failure mode, their effects, and causes are identified. After scoring according to the rating scale given in Table 1 and Table 2, criticality assessed and the action plan is inferred. When the S-FMECA is performed, a dedicated platform is used. Figure 4 shows an example of the S-FMECA interface. The platform may vary somewhat, depending on the type of evaluation that will be made, and on the specific user needs. The platform is divided into three different parts: the project definition, the product analysis, and the S-FMECA analysis. The platform also works as a medium of documentation, of great importance for the follow-up evaluation of an FMEA.

3.3.2. Case study

A combination press tool is a die in which a cutting operation and a non-cutting operation on a part is carried out in one stroke of the press. The case study deals with the development of a combination press tool to be used for the manufacturing of a cement-bagging nozzle. The press tool performs a double-lancing operation, which is stamping and drilling, on a single stroke. The case study was taken to autonomously manufacture spare parts within the company. The frequency of changing the nozzle being high, purchasing from a supplier slows down the production as delivery times are long.

STEP 1: Eco-design Project

This case study focuses on eco-designing a combination press tool to be used in the fabrication of the cement-bagging nozzle. The available press machine to consider in the manufacture of the combination press tool is a Kawasaki mechanical press with a capacity of 25 tonnes. The additive manufacturing is used in a selection of the combination press tool components.

STEP 2 & STEP 3: Structural Decomposition & Identification

After data collection, an S-FMECA multidisciplinary working team conducted a brainstorming session. Farthest of this session, a list of failure modes, their effect, their causes, and their detectability were addressed. An extract of the analysis as generated by the S-FMECA database is given in figure 5.

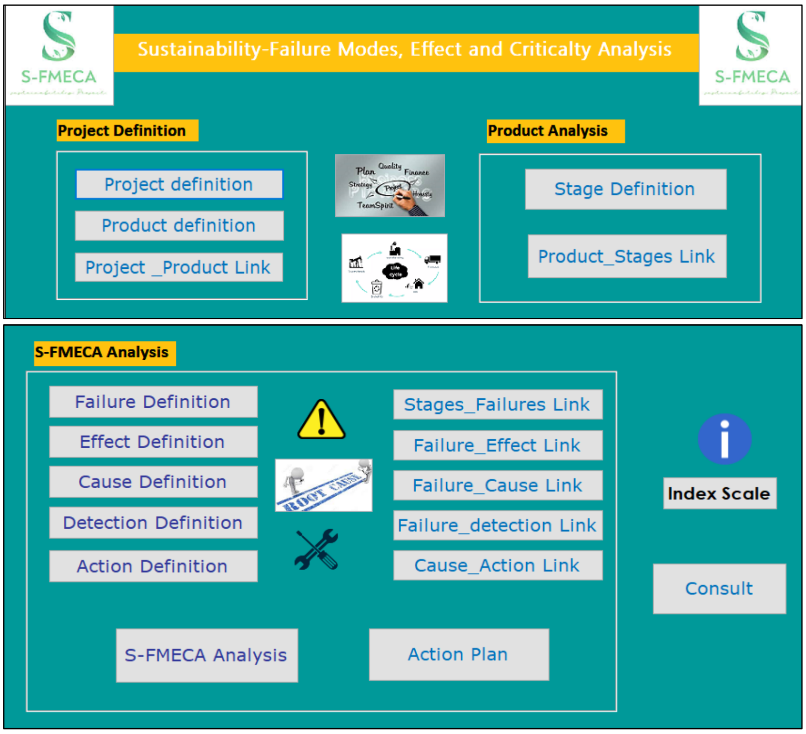


Fig. 4. Snapshot of the S-FMECA « standard GUI »

id_project	8		
Project_name	Combination press tool		
Product_Name	Punch		
Stage_Name	Design		
Failure Modes.Designation	Effect.Designation	Cause.Designation	Detection.Designation
Design not convinient for AM	AM time too long	Conventionnal manufacturing	Investigation needed
Wrong AM machine parameters	AM time too long	DFAM not applied	Later stage
Punch material selection	Effect on Environment	Bad identification of technical	Investigation needed
Mechanical resistance	Time and money waste	Fracture toughness not suitab	Later stage
Punch material selection	Effect on Environment	Material availability	Investigation needed
Mechanical resistance	Time and money waste	Fatigue endurance not suitabl	Later stage
Mechanical resistance	Time and money waste	Not sufficient mechanical stre	Later stage

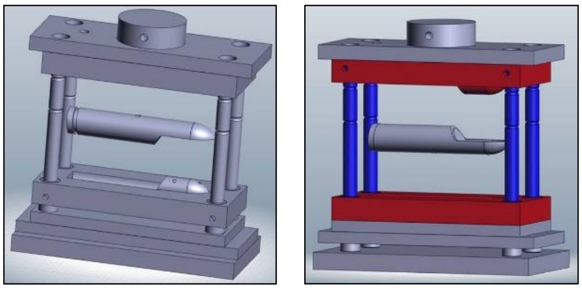
Fig. 5. Combination press tool FMEA analysis (Snippet)

STEP 4 & STEP 5: Valorisation & Actions Plan

At this level, a rating of the three criteria (frequency, severity, and detection) using suggested rating scales and sustainability indicators (Table 2) is performed. In addition, the failure modes causes are classified in descending order of their automatically calculated criticalities. Actions are associated accordingly, thus constituting an ordered list of actions to implement to succeed in the eco-design project. Figure 7 shows an extract from the valorisation stage and the action plan for a successful combination press punch design. A functional analysis led to the ideation of two possible solutions given in Figure 6. After the assessment based on the design requirements, solution 1 has been selected. An initial design is proposed accordingly (Fig. 8). The die and the punch are considered to be additively manufactured in low alloy steel.

STEP 6: Collaborative S-FMECA Implementation

At this level, data need to be collected from CAD, TO, CAM, CAPP, PLM, and LCA software. Actually, a topology optimization using nTopology© software has been performed for both parts: the die and the punch. The corresponding weight reduction is given in figure 9. The environmental impact assessment was carried out via the calculation of the Eco-Indicator 99 (IE99) using the ferro-metals materials IE99 [37].

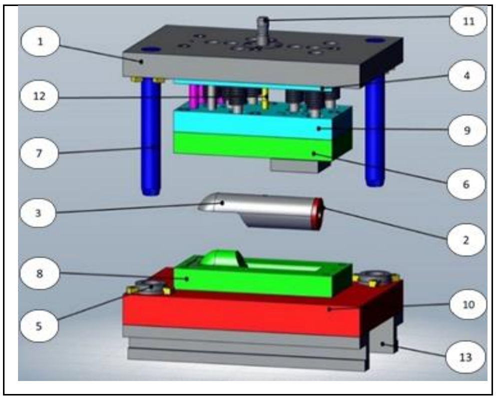


Solution 1 Solution 2

Fig. 6. Design ideation.

id_project		8				
Project_name		Combination press tool				
Product_Name		Punch				
Stage_Name		Design				
:riticality	Failure Modes_Designation	Cause_Designation	:ct_Index	se_Index	:ion Index	Action_Designation
125	Mechanical resistance	Fatigue endurance no	5	5	5	Choice of materials-Ashby charts and validatior
125	Mechanical resistance	Not sufficient mechar	5	5	5	Choice of materials-Ashby charts and validatior
100	Wrong AM machine parameters	DFAM not applied	5	5	4	Topology optimization
80	Punch material selection	Bad identification of t	5	4	4	Apply E-QFD technique
30	Mechanical resistance	Fracture toughness nc	5	3	2	Choice of materials-Ashby charts and validatior
15	Design not convinient for AM	Conventionnal manuf	5	3	1	Consider the hybrid machine alternative
12	Punch material selection	Material availability	3	4	1	Material Supplier survey

Fig. 7. Extract from the valorisation stage and the action plan



1 Upper die shoe
2 Core
3 Workpiece
4 Drilling Punch Holder
5 Guide Bushing
6 Punch
7 Guide pin
8 Die
9 Punch Holder
10 Die Holder
11 Standard flanged shank
12 Drilling punch
13 Lower Die Shoe

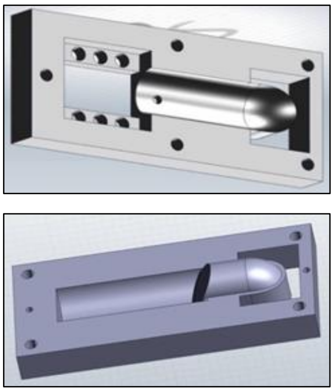
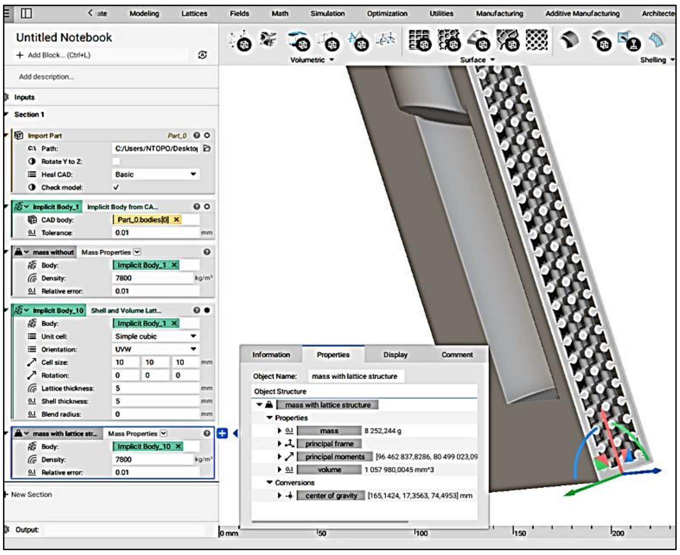


Fig. 8. Combination press tool CAD design proposal



Topology	Die		Punch	
	Weight [g]	IE99 [mPt]	Weight [g]	IE99 [mPt]
Without Lattice structure	11 828	1 302	9 397	1 034
With Lattice- Simple Cubic	8 253	908	6 742	742
With Lattice-Hexagonal Honeycomb	11 474	1 263	9 163	1 008
With Lattice-Diamond	10 156	1 118	8 259	909

Fig. 9. Topology optimization with lattice generation

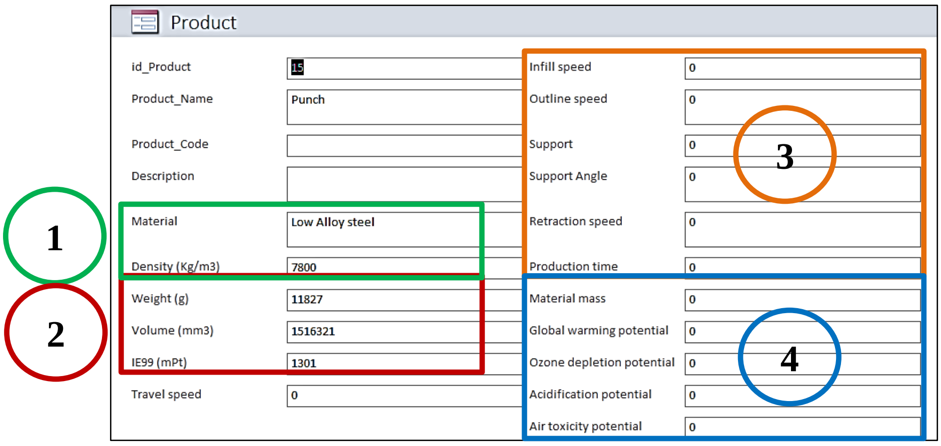


Fig. 10. Basic information needed for collaboration

Three types of lattice structures were experimented with: Simple Cubic, Hexagonal Honeycomb, and Diamond. As expected, the weight and the environmental impact are lattice structure dependent. The Simple Cubic one gives the minimum mass. To validate this choice, a numerical simulation by FE must be carried out to verify the good mechanical resistance, which has just been ranked first in our action plan.

Subsequently, we re-evaluate the assigned three criteria indexes, and the failure modes causes are classified afresh in descending order of their automatically calculated updated criticalities. A new action plan is generated accordingly. Thus, we iterate until convergence towards the optimal solution.

It should be highlighted that we had to calculate the IE99 to manually incorporate it into the product analysis interface in the S-FMECA platform, as shown in figure 10. Zone 1 is filled in from the initial definition stage of the product. However, zone 2 can only be filled when the IE99 has been calculated in the DDS phase. The product mass is needed to calculate the IE99. We get it manually from the TO software. Whereas if a collaboration is established between the S-FMECA application and the topological optimization software, it would be possible to automate this calculation. The third zone will need to collect data from the slicing software and the AM simulation software. However, the fourth zone will allow the environmental impact assessment using ReCiPe 2016 (Hierarchist) method [38] in order to calculate the different impact categories. Hence, our proposal of an S-FMECA-based collaborative methodology to automate the calculation.

3.4. Collaborative Methodology Proposal

Either connecting LCA eco-design software with CAD and PLM systems or CAD with CAE, CAM, and TO software, have been addressed by several researchers and take place most of the time via neutral files (STEP, IGS, STL, etc.) or specific files like Excel© (xls, csv) or code-G format. What we propose is to not limit ourselves to two-by-two data exchanges (shown schematically as a dotted line in Figure 11) but to move towards a central element, which is the S-FMECA tool that communicates at the same time with all the used software, as schematized in solid line in the figure 11.

The S-FMECA application will be used to collect data from all stakeholders, update the indices of the three criteria correspondingly, calculate the new criticality, and update the action plan congruently.

4. RESULTS AND DISCUSSION

The paper introduces a new eco-design for additive manufacturing methodology, summarized in Figure 12, which takes into consideration all the product life cycle stages from the early design stage till the end-of-life stage. The manufacturing stage as well as the usage one, as intermediate stages in the product life cycle, are taken into consideration in advance from the early design stage.

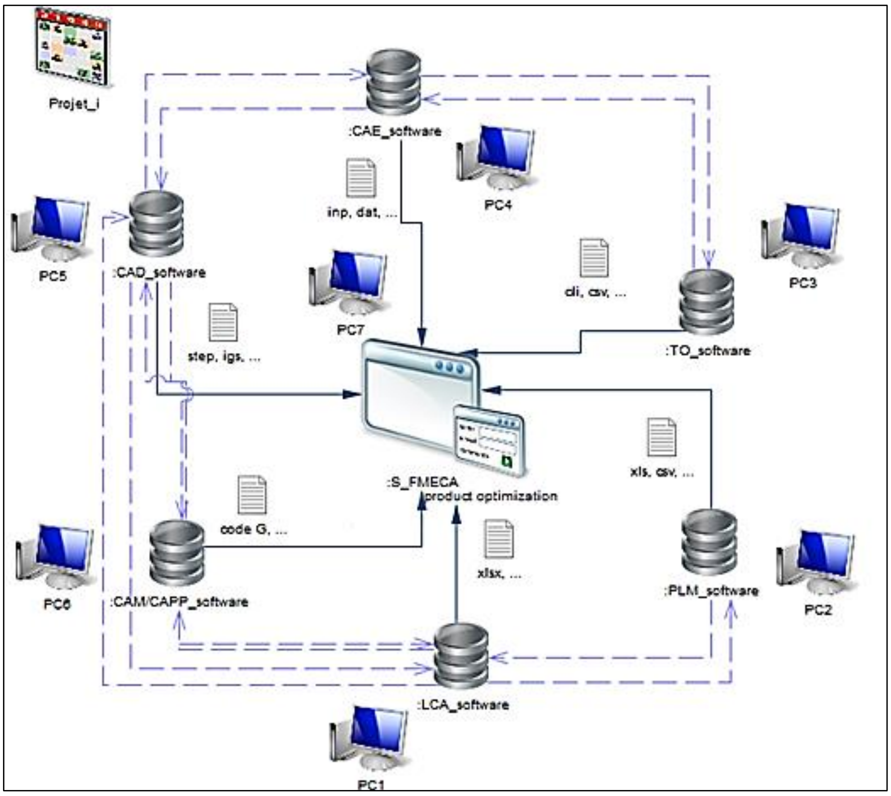


Fig. 11. Collaborative design proposal for AM

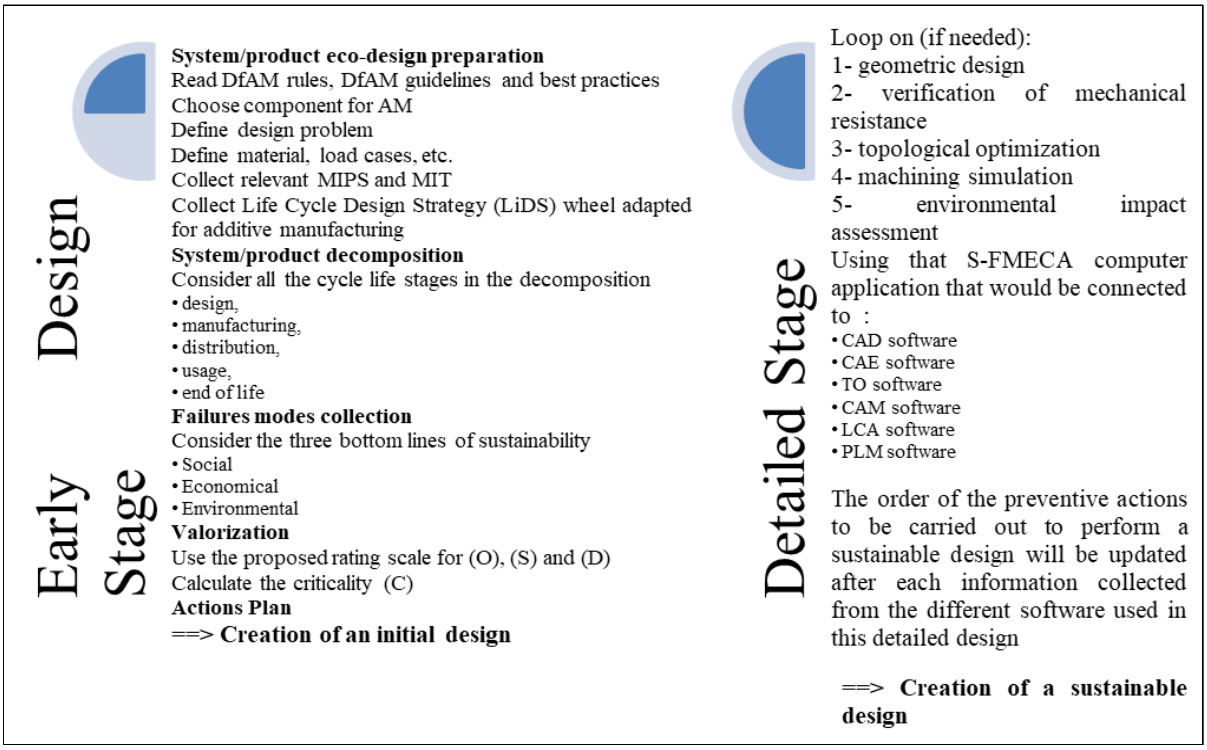


Fig. 12. Eco-design for AM methodology

The proposed S-FMECA-based methodology helps the designer to prioritize the causes of failure and to put in place an action plan. This is to allow the designer to act preventively since he would anticipate the failures that are likely to appear during the whole product life cycle. Consequently, the designer will be able to reduce the environmental impact from the start of the design process. Our S-FMECA tool and methodology proposal arises from the following observations:

- The assessment of environmental impacts is carried out mainly via LCA software. As the use of this software is suitable for the detailed design phase, the designer's leeway to reduce the environmental impacts is, therefore, limited. It would be wise to develop a decision-making support tool that can be used in all design phases to make green-conscious choices.
- The general limits of CAD, CAM, and PLM solutions are their inability to manage the entire product life cycle information. CAD is mainly limited to form feature data and PLM merely manages encapsulated objects and not embedded data.
- Toolpath optimization is a key factor for efficient and accurate manufacturing with CAM software, helping to reduce manufacturing time and increasing productivity. Such optimization must be carried out with an objective of better sustainability.
- Topology optimization is a key tool in design for additive manufacturing that allows lightweight and mass material optimization. Therefore, it is essential to establish collaborative connections between CAD, CAM, TO, and LCA software to iterate in order to decrease the environmental impact.

The proposed integrated S-FMECA-based framework would provide a solution to manage the whole product life cycle information while communicating, during the different design stages, with the various stakeholders in the design, manufacturing, and disposal of products. Thus, a multiple views product gathering would structure environmental information to optimize the product’s environmental performance.

5. CONCLUSIONS

After a general introduction related to the need for an integrated design for additive manufacturing methodology, the paper presented the theoretical concepts of eco-design and DfAM as well as the eco-design for AM tools and methodologies.

An integrated eco-design for AM methodology proposal was afterward introduced to fill in the detected research gap. A basic S-FMECA tool was then implemented to contribute to the development of the integrated CAD, CAM, TO, LCA, and PLM eco-design framework.

Once the S-FMECA tool was established, it was then applied for a combination press tool design. Interestingly, the new framework was able to:

- Provide a genuine proactive methodology to moderate, even avoid, failure modes in the early design phases of the design for the AM product development.

- Help the designer to integrate sustainability issues within the FMECA in the EDS as well as the DDS allowing green-conscious choices.
- Rank in descending order of criticality the failure causes so that countermeasures could be integrated with a preventive action plan.
- Update the preventive action plan following the provision of new information becoming available when we move forward in the design and manufacturing process.

The results are promising regarding the technological feasibility of the approach. The whole framework implementation should, however, be studied in the future. Implementing the collaborative design for AM data interoperability between the software using XML could allow the automatic transfer and demonstrators need further tests with the industry to explore the methodology's usefulness.

The authors plan to develop such an integration of environmental aspects using the S-FMECA platform that supports the proposed collaborative design approach. A more appropriate programming language would be considered for the holistic framework development.

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