A methodological proposal to link Design with Additive Manufacturing to environmental considerations in the Early Design Stages

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Abstract Additive manufacturing is an innovative manufacturing process that enables rapid manufacturing of functional products and parts. On the other side, considering environmental aspects in design is beneficial as it leads to lower costs, improved product quality, new business opportunities. Thus, in order to foster the potential of AM in product innovation and product manufacturing in the light of environmental concerns, a new design method is necessary. This paper proposes a method in the context of Design with Additive Manufacturing, to take into account the specificities of this manufacturing process in a Design to Environment approach. The method is focused on the Early Design Stages (EDS) of the product development process, which are crucial not only for choices regarding the product characteristics but also for the environmental parameters that need to be taken into consideration. The implementation of the proposed method in creativity session of the EDS underlined the need for dedicated supports in terms of environmental decisions. More and specifically the need for providing tools to capitalize the decisions made focusing on each Life Cycle Stage of the product was identified as a requirement for this support.

Keywords Design with Additive Manufacturing · Design to environment · Life cycle models · Eco-design

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1 Introduction

In today's product design, there is a real need to communicate and collaborate on design concepts and to share data interactively in a real-time. However, a comprehensive system for developing new products that satisfies all the necessary requirements is still unavailable [1]. The early design phases (EDS) correspond to a series of crucial steps for the product. It is well known that at this earlier stage, every decision on the product engages the majority of the future costs of design, production, assembly, maintenance, and disassembly [2]. The interactive product design is of major economic and strategic importance in the development of new and innovative industrial products and processes. Interactive design is especially developed to support the knowledge modeling in preliminary design. In interactive design, the creation of a product is considered to be constrained by three factors: the expert's knowledge, the end-user satisfaction and the realization of functions [2]. In the early stages of design, various experts from different fields are working together in order to provide a solution. Hence, knowledge is divided between these experts and there should be structures to share this knowledge [3]. However, at the time of writing just few research propose to link Design with Additive Manufacturing knowledge to environmental considerations in the EDS, especially in an interactive way. A first case-study is necessary to deploy later a customized solution tailored to the needs of designers and experts. Hence, we propose in this paper a method in the context of Design with Additive Manufacturing (DWAM) [4], to take into account the specificities of this manufacturing process in a design to environment (DTE) approach. The method is focused on the EDS of the product development process, which are crucial not only for choices regarding the product characteristics but also for the environmental parameters that need to be taken into consideration.

During the product design and manufacturing processes, experts from different backgrounds such as design, engineering, or ergonomics are involved together to reach the same goal: design a product with specific requirements, including environmental performances to obtain. All of these experts need to be supported by available methods and tools to take into account all those business constraints, including eco-design ones [5]. The knowledge required in order to face those constrains needs to be linked in a dynamic manner [6]. In this way collaboration, or in other words different experts sharing resources to reach the same goal, has to take place.

This research focuses on both manufacturing and product designer experts willing to improve the environmental performance of the product. The need for a cross functional approach, in which all actors contribute and commit to environmental improvement form the earliest stages of design and throughout product development has long been identified (ISO 14006 2011) [7]. Therefore, links between manufacturing processes and environmental indicators are required. eco-design practices need to be implemented both in product designer's activities and supporting management functions. Eco-design is a method which aims to achieve environmental impact reduction throughout the product's life cycle, without compromising other essential criteria (e.g. performance, cost) [8]. However, difficulties in eco-design implementation and management have hindered this process from being implemented worldwide and various obstacles and barriers still need to be addressed [9].

In general, towards the integration of the environmental parameters into the product designer's parameters, the following issues need to be considered: (1) the compatibility of environmental and product design objectives, (2) the importance of environmental integration as early as possible during the design process and (3) the environmental knowledge needed to perform eco-design. In addition, there is a need of product designer methods and software (e.g. CAD) and environmental assessment methods and software (e.g. LCA) interoperability. They need to exchange and use information from each other. It is essential in order to practice collaborative eco-design [6], in other words, to *Design To Environment* (DTE).

In this contextual framework, the research question of this paper is "how to link DWAM and DTE in order to foster the consideration of the environmental impacts of every lifecycle stage of the product under development in the EDS in engineering and design education".

This paper provides: (1) a description of the context of the research (namely the process of creating the proposed method and the activities involved), (2) the major functions that would support the dynamism of the DWAM and DTE linkage are identified, and iii- the observed issues are presented. Then, a first version of the method is proposed. Two creativity sessions are conducted, the second one implementing the method proposed, aiming to observe and compare each actor's output according to specific criteria. The method is then updated in a second version and its efficiency and usability is examined by experts in AM processes and in Environmental impact assessment.

2 State of the art

2.1 AM and sustainability

Additive Manufacturing has many advantages, especially dealing with its integration in product design. Gibson et al. [10] call it "AM Unique Capabilities", and classifies it in four categories:

- Shape complexity: it is possible to build virtually any shape.
- Hierarchical complexity: features can be designed with shape complexity across multiple size scales.
- Functional complexity: functional devices (not just individual piece-parts) can be produced in one build.
- Material complexity: material can be processed one point, or one layer, at a time as a single material or as a combination of materials.

The material complexity, allowing more specifically to optimize the shape/function couple of a product, will be the object of more attention because it is one of the influential parameters in eco-design.

As AM is promising in regards to sustainability, it is important to facilitate the exploitation of the benefits it provides. Specifically, its innovative nature could lead to minimizing environmental impacts by inventing new systems consuming less energy and resources, while improving economic models and benefit to users. As argued by Giurco et al. [11]. AM can contribute to sustainability in many ways, which include facilitating the extension of product use lifetimes, the design for disassembly, helping address issues of resource dispersion and reshaping the recycling process. According to Despeisse and Ford [12] and Mani et al. [13], potential opportunities of the AM process in regards to sustainability could be:

- Reduced overall amount of resources consumed, due to the additive nature of the process, making the whole system less energy intensive;
- Less waste material, as fewer parts and more optimized geometries are produced;
- Easier End-of-life product recycling and conversion of by-products into filament for the AM machines, commonly known as waste up-cycling;

- Manufacturing and Remanufacturing for maintenance, for example in situ repair of damaged parts to extend operational life;
- Shorter supply chains and localized production, potentially leading to logistic environmental impacts reduction;
- Shift from economies of scale to smaller production of customized goods at more affordable prices;
- New service-based business models;
- Products functionalities and products usages in adequation with the user needs, if users are also the designer and manufacturer of those specialized products.

Limited research exists examining the environmental impacts of this technology that engages new designers and users. A lack of available lifecycle data results in a difficulty to conduct accurate environmental impact analysis, or even full life cycle analysis (LCA) in a perspective of using AM technologies [14] to support a product lifecycle. On the AM process itself Mani et al. [13] highlighted the lack of a measurement standard for total AM energy inputs and losses. In fact comparing AM environmental performance to common manufacturing machines makes not much sense in eco-design as the product manufactured should be considered within its total lifecycle regarding its functional performance to a user. In this view Barros and Zwolinski [15] showed that the user profile of AM technologies much influences the whole product lifecycle environmental performance. Gaining AM expertise with the machine goes by pair with understanding the potential environmental consequences of the design choices taken. Both support Design(ing) to Environment AM based products.

2.2 Generic process of LCA

Expert methods are required to assess the product environmental impact in regards to all activities included in its lifecycle stages including its manufacture. The LCA standard method (ISO 14040 2006) [16] is a multi-criteria and quantitative multi-impact environmental assesment, a "compilation and evaluation of the inputs, outputs [material and energy flows] and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040 2006). It is known as the most mature method for the evaluation of impacts, however its application through a dedicated LCA tool to support product designers to eco-design products is difficult, because LCA tools (e.g. Open LCA, SimaPro, Gabi) are expert tools that can be "disconnected" from product designer's activities [17]. To provide a holistic approach, including for process evaluation [18], full and streamlined LCA's databased tool need to integrate AM material and energy flows or allow some "process cards" customization to allow designers to assess the AM based products lifecycle environmental impact in their specific manufacturing context, including:

- The goal and scope definition (e.g. system boundaries, product functional unit—LCA stage 1);
- The lifecycle inventory for which knowledge about the product and access to databases are essentials (LCA stage 2);
- The impact assessment resulting from the aggregated inventoried material and energy flows at each life cyclestage (LCA stage 3);
- Global and local environmental impacts (e.g. climate change potiential, ozone depletion, toxicity, resource depletion) which rates are interpretated to formulate recommendations for product lifecycle environemental improvements (LCA stage 4).

2.3 Creativity session

Many tools are available in the Early Design Stages, to brainstorm and foster innovation. Among these, creativity sessions are widely used to produce ideas for new products (for e.g. Cluzel [19]). In general, a creativity session includes four phases, namely the goal definition, the divergent phase, the convergent phase and the evaluation. Various tools can be employed in each phase of the creativity session. During the divergent phase, brainstorming activities are used (e.g. "Purge" method): participants are asked to come up with as many ideas of existing products with the same functions as possible. Afterwards, the convergent phase aims to narrow the creative production and the participants are asked to produce idea sheets. The idea sheets are evaluated in the last step of the creativity session.

The consideration of the environmental parameters in the EDS of the DFAM process can be integrated by providing to the participants tools aiming to stimulate their creativity in the EDS while taking into account both the environmental impacts of their decisions as well as the restrictions of the AM processes available.

2.4 Creativity, additive manufacturing and environmental aspects

In engineering design, experts are challenged to create innovative products that fulfill society's demands and environmental issues. The basis towards this goal is provided through engineering education, for example, by introducing learning games in education such as the one proposed by Galaup et al. [20].

AM stimulates designers creative skills, as complex shapes which would otherwise require more machining operations are now possible. Bearing this in mind, there could be a huge benefit from coupling AM and Design to Environment.

However, industrial designers might only have a general idea about "sustainability", wondering how to implement it, especially when the client does not raise the subject [21].

2.5 Issues

In the product design, multidisciplinary teams of expert strive towards designing the product, according to the specific goals set. In this process, the role and activities of the Env. expert are particularly interesting to investigate, due to the fact that their role is more formalized in the evaluation phase, after the product's detailed information are available. Bhander et al. outline the problems that exist before environmental considerations can be addressed in product design and acknowledge that designers are not often in direct contact with Env. experts during product design [22]. They argue that the designer must be supported to make environmental decisions in product design. Van Hemel et al. summarize the eco-design barriers in companies, among which, one of the most frequently occurring barriers is that eco-design is "not our responsibility" on behalf of the professionals [23]. This barrier is not only frequent, but is also one of the barriers that make eco-design impossible for companies. Even though this and other barriers were identified approximately 20 years ago, they can still be true for the majority of companies. However today with environmental legislations, European directives, standards etc., companies are more and more aware of their responsibility. Still environmental tools/methods are not well integrated in the product design process. These facts underline the importance of investigating and facilitating the interaction among experts in the EDS, when designing to environment. In this context, the following issues have been identified (Table 1), and the respective functions are proposed in order to address each issue.

3 Case studies

No relevant method exists to assist the experts for more environmentally friendly DFAM. The objective is to provide a method to the designers intervening during the EDS that reinforce the fundamental lacking functions presented in Table 1.

Two creativity sessions are carried out both following a standard procedure for creativity sessions [5]: (1st) without any method proposed; (2nd) with the proposed method. Five different experts participate in each session, namely an AM expert, an Env. expert, an Ergonomics expert, a Mechanical Engineer and an Industrial Designer. Both sessions have the same structure: (1) goal definition; (2) brainstorming phase (purge); (3) idea sheets creative production; (4) evaluation of the idea sheets; (5) providing feedback about the experiment followed to the creativity cession animator by answering to a questionnaire. The objective is to compare the output of each session with the minimum bias possible, in order to evaluate the usability and usefulness of the method proposed regarding the lacking functions identified in Table 1. In both creativity sessions, the participants were asked to design a goodie for the students of the École Nationale Supérieure d'Arts et Métiers (ENSAM), i.e. a small toy or gadget, which is usually distributed free of charge from companies for marketing purposes, disseminating the company (or ENSAM) identity and values, for a minimal of environmental burden.

3.1 Method requirements to provide fundamental environmental functions

Lindahl [24] analyzes some eco-design methods and tools requirements addressed to engineering designers in the product development process. The method or tool needs to be intuitive, logical, easy to understand and to communicate with, not requiring a detailed user manual. Furthermore, it needs to be adjustable, requiring a minimum of setup time for the designer's cooperation to provide the requested data to use the tool. Visualization of results through software can be relevant. The method (or tool) must guide the users to investigate the environmental impact causing the results obtained. Complementarily, Tyl et al. summarize some eco-innovation tool requirements, which should abide with many disciplines requirements, such as design, engineering, ergonomics and even knowledge management [25]. Such a tool must allow the exploration of ideas, foster collaboration, generate confidence to users, be easy to use, and it should allow some performing ideas generation. Vallet et al. [26] underline the importance of such tool evolutions through collaborative learning leading qualitative tools evolving toward quantitative ones.

The proposed method in the experiment seeks to satisfy those authors' requirements, while satisfying Table 1 functions. Checking the conformity of this method regarding those requirements and functions are the object of the questionnaire given to the participants (including experts' in the field of AM and Environmental impact assessment) in (5) (cf. the previous section). While Tyl et al. refer to the requirements of specific tools, these are in essence also the requirements that the proposed method is aiming to achieve. As the method is proposed to be used by multidisciplinary teams, with different areas of expertise, the method must not be too complex to understand and utilize, and it must offer guidance and stimulate creativity. As Vallet et al. state, collaboration is one of the most important aspects of the tool, therefore considering the need for exchange of knowledge among the experts that participate, the development of such a method and its utilization needs to be collaborative. Baouch et al. emphasize that eco-design knowledge has to be co-constructed in order to accommodate the needs of the various stakeholders involved [27].

Table 1 Issues occurring in the EDS concerning environmental integration and proposed method

Category	General issues	Refined issues	Fundamental lacking functions	Method
Experts involved	Each expert has different activities, knowledge, rules, tools, goals and does not always share the same concepts definition	Env. expert's role: not yet fully integrated with the others during design	Environmental experts' knowledge sharing for collaboration with others	Collect experts' knowledge;
			Identifying inputs/outputs of activities (e.g. AM, usage)	Match inputs/outputs of their activities
Early Design Stages	In the EDS product characteristics are not yet completely specified	Quantified environmental analyses can be difficult in the EDS	Identifying in which EDS activities environmental integration can occur	Identify EDS activities in which the Env. experts could be involved and share information, concepts, *etc*
	Environmental analysis requires a lot of information for the product			
Design process	Product design process integrated with environmental considerations in the AM EDS is not yet formalized	There is no alignment between the Env. expert's and other expert tasks at the EDS	Mapping the experts' activities to align env. Expertise and other expertise information exchanges at the EDS for a product lifecycle based on AM usage	Link EDS with environmental considerations through the process tasks, timelines, "crucial" information exchanges
	Env. Experts' moments to interact, tool/support format to use, level of detail to address to other (etc.) are unclear			
Engineering-design education	Environmental considerations and product design and engineering are many times taught separately.	Lack of environmental and lifecycle considerations in curriculum for the EDS/AM	Identifying how environmental considerations can be included in creativity sessions, specifically for AM based products	Propose an env. integration method during creativity sessions at EDS including AM and lifecycle considerations

3.2 First creativity session

In the first creativity session, the five experts worked together as a group to "design an innovative goodie for the ENSAM taking into account environmental considerations as much as possible" (Design Brief). A goodie was chosen as a purpose to design a simple use case product with a limited amount of functions to be fulfilled. The Env. expert participated to the session via a visio-conferencing device. The session lasted one hour:

(1) Goal definition: 5 min
(2) Purge: 10 min
(3) Creative production: 30 min
(4) Best idea selection: 10 min
(5) Feedback: 5 min

The participants produced in total three concepts reported in 3 idea sheets: a finger cuff, a cufflink, and a "trophy". The cufflink was selected as the best idea (Fig. 3, left side). The AM processes enable creating a finger cuff with a stiff structure and a soft texture that could fit every finger. This capacity to be personalized was identified as a key issue during the session—stage (4).

The problems encountered by participants during the creativity session expressed in stage (5) using questionnaires are presented in the following sections.

3.2.1 Limitations of the study and bias

Sources of bias influencing the results of the creativity session have been identified as the following:

- Human interaction and communication issues: as in similar sessions being carried out in the industry, participants interacting by visio-conferencing systems have more difficulties to interact with other and to be heard. Additional common social issues affect the participant's integration in the group: charisma, loud voices, etc. A cession moderator is necessary to reduce those biases.
- Unfamiliarity with creativity sessions: lack of experience in the way creativity sessions are conducted can hinder the efficiency of the session and limit the range of possible outcomes. Be trained in advance to the tools and methods used during the session helps participants gain efficiency during creativity sessions.
- Understanding other expertise: at some point during this session the ergonomic expert put himself aside, unable to identify the link between the product ergonomics and environmental performances. The debate stage offers an opportunity to participants in making explicit links between the key parameters they use regarding the global performance requested.

3.2.2 Information exchange between the experts

The participants engaged in lively conversation during the creative production concerning each idea, and each one provided information in the form of guidelines, examples, and general advice. However, they identified the following problems to properly interact with others, in most cases due to a lack of information on particular topics. Although the Env. expert needed to define the functional unit of the product to provide a precise advice on the environmental aspects, he was constrained by the undetailed information about the product at this stage. The experts expressed their lack of knowledge about each other's domain of expertise.

3.2.3 Information about the AM processes and the AM associated materials

All of the experts requested information about the possible materials to use through AM processes. For example: the Env. expert suggested ABS or another renewable material in case of a limited lifespan of the goodie. A list of the AM associated materials and the possible finishing processes were therefore needed to envisage this situation. The Ergonomics expert then wanted information about the texture and finishing options associated to materials and AM processes. The material and mechanical experts needed to refer to material properties information, and were looking for visual forms, such as pictures, animations, videos to show to others.

The Env. expert, the Industrial designer and the Mechanical Engineer all needed more information on the available AM processes. The Env. expert underlined the need for an overview of the available AM technologies with associated resource consumption (material, energy, water, gas, etc.), while the Industrial designer needed schemas of the available AM technologies in order to understand the manufacturing restrictions associated to possible design constraints and opportunities.

3.2.4 Information about the environmental parameters

All of the experts expressed the need for more information on the relevant environmental parameters unanimously, since the focus of the session was to minimize the environmental burden of the goodie. The Env. expert needed information on the environmental impact of material extraction, processing and end-of-life route for each AM technology. He suggested a comparison of processes and materials including the order of magnitude of the impacts. He requested information about several significant impact indicators showing the contribution of each type of materials or processes (e.g. toxicity to human, to water ecosystem for Fused Deposition Modeling technologies). A visual representation of such environmental performance were requested by other experts allowing them to consider the environmental aspects in regard to their own expertise.

3.3 Proposition of a method to support environmental decisions in the Early Design Stages

A method including four tools has been proposed to support experts' environmental decision making during the creativity session regarding feedbacks obtained during the first session. The four tools are integrated in the creative production phase (3) and in the evaluation phase (4) of the creativity session and are meant to provide participants the lacking information identified previously to help expert collaborate together around the environmental performance of the emerging concepts.

*L*ifecycle considerations this approach seeks to enlarge the typology of the product itself by stimulating considerations of the whole product lifecycle. Based on LCA basis manufacturing processes, materials, usage, end-of-life strategies (etc.) have to be considered together in EDS to make environmental decisions in regards to each expertise (ergonomics, mechanics, material choices, aesthetics, etc.).

*M*aterial and energy flows a LCA takes precisely into account the material and energy flows linked with the manufacturing process. This method proposes to inform participants about AM process basic characteristics: material and energy consumption, type of raw material, finishing processes. The characteristics of the materials, the emissions for their extraction and the possibilities for their end-of-life are presented in this first version. *T*iming finding the best moment to use the proposed tools is an additional parameter considered. The first three tools supporting AM processes understanding should rather be used during the creative production of the creativity session (stage 3). Then the fourth tool would be used in the evaluation phase of the creativity session (4) to reassess which goals—environmental and not—have been fulfilled or not, and stimulate the generation of new ideas for improvement.

*T*he first tool proposed to be included in the creativity session is the lifecycle design strategies (LiDS) wheel, adapted to the AM technologies (Fig. 1). The use of this tool aims to support the participants in their environmental decisions along the product lifecycle stage and is intended to stimulate the generation of creative solutions rather than restrict the possible design outcomes. The wheel was proposed by Hemel and Brezet in 1997 and is in essence a visualization tool used in order to select and communicate eco-design strategies. It provides a range of very simple actions that can be taken in order to improve the environmental performance of a product [23]. The wheel is used to select the best actions that improve the environmental performance of the product on each of the areas that it includes, which represent the product lifecycle stages. These are new concept development, Materials selection, Materials usage, Distribution, Product use, Optimal life and End of life. A dot is put in each stage, according to the assessment, the dots are joined, and the resulting area is used to identify problems and produce ideas for improvement.

This tool is chosen as it can be used in the early stages of product design, in which there is still a high level of abstraction. Lofthouse et al. have used this wheel in the Information/Inspiration website, a tool developed to provide guidance to industrial designers that are involved in eco-design as it is adapted to early design stages and to the industrial designers knowledge and activities [28]. The tool is modified to integrated considerations about AM and AM design constraints (Fig. 1: material usage considerations for AM for instance).

*T*he second tool takes the shape of a card to provide to participants an overview of the existing AM technologies and their basic characteristics (Table 2), to help them choosing the most suitable for the specific product. The AM expert participating to the session can add technical information if required by participants. Apart from an overview of the AM technologies, the table contains information on the material capabilities of each technology, the material state, the energy consumption, the use of inert gas and water and finally the associated post-processing methods. For example, in the post-processing of a part manufactured via the Polyjet AM process requires the consumption of considerable quantity of water, even for small parts. Thus, by providing the information on inert gas and water consumption, the participants are encouraged to debate to best align the AM process characteristics to the product requirements during each lifecycle stages.

*T*he third supporting tool (an extract is presented in Table 3) proposed is a materials card, which includes information about the most common materials used in AM technologies. These cards aim to give to the participants, the necessary background on common materials used in AM and their properties. This proposition aims to cover the participants' need for more information on the materials, which was expressed by the participants of the first creativity session. The table includes information on embodied energy, CO_2 footprint, recyclability, down-cyclability, energy recovery, landfill options and bio-degradability of the respective material.

After the creative production, the tool proposed to be used is a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis. This tool is proposed to be integrated in the evaluation phase, in order to assess whether the goals—environmental and not—have been set and in which aspects the product might still need improvement. The SWOT analysis is centered on evaluating the ideas in consideration of the whole product lifecycle, including the

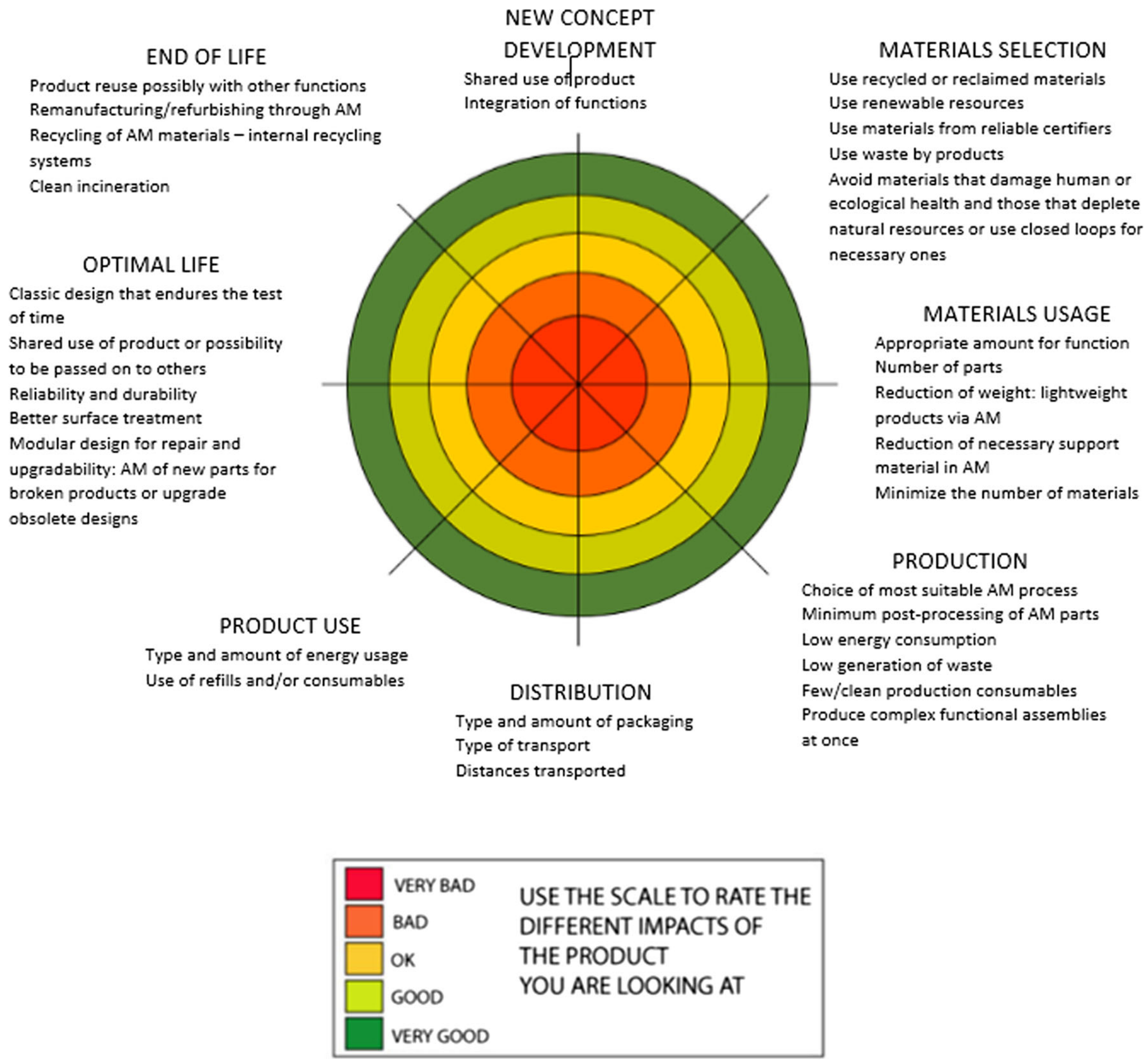

Fig. 1 LiDS wheel adapted for additive manufacturing

AM process. The tool reinforce the participants assume a holistic view of their decisions and evaluate the environmental performance of the product on every aspect in stage (4).

The whole method synopsis (Fig. 2) has been applied in a second creativity cession presented in the next section.

3.4 Second creativity session

The second creativity session implemented the proposed method. The four tools were sent to participants before the creativity cession. The participants did not express any difficulties in understanding the material provided but expressed the opinion that some of the information might be too complicated to interpret if their expertise was not represented during the creativity cession. They also requested a better understanding of the cession goals, and the way the results would be used in stage (1).

During stages (2–4) of the cession the moderator regularly provided encouragement and reminder to participants to consider the environmental parameters and make environmental decisions about the product.

Three ideas came up during the session, a bookmarker, a key protection (Fig. 3, right side) and a cup holder. The first idea, **the bookmarker**, was proposed to be manufactured via sheet lamination, reusing paper sheets. The participants concluded that this is an environmentally friendly goodie as it would be made with reused paper and can be incinerated in its end of life.

The second idea is a **key protection**. This goodie was proposed by the Env. expert and the AM expert to be manufactured via FDM. All experts provided their input to decide the type of material (ABS or PLA) to be used.

Table 2 AM processes table (extract)

No	AM category	Am technology	Material capability (metal/ polymer)	Material state	Energy consumption rate (ECR) (kWh/kg)	Inert gas	Post- processing method	Water	Multi- material (Yes/No)
1	Binder jetting	Binder jetting (BJ)	Both	Powder		Yes	Part curing/sintering	No	Yes
2	Direct energy deposition	Electron beam melting (EBM)	Metal	Powder	17.00–31.00 (Metalic powder)	No	Sand blasting thermal processing surface finish	No	No
3	Material extrusion	Fused deposition modeling (FDM)	Both	Liquid	23.10–346.43 (ABS)	No	Water solution surface finish	Yes	No

The first idea was to use PLA, as it is biodegradable. Then the participants decided that ABS would provide a better durability. The Env. expert proposed that only one color could be used for the product to facilitate its recycling at the end of life. The Mechanical Engineer proposed to put more emphasis on the shape of the goodie, since it has no effect on recycling as opposed to the use of color. The AM expert envisaged to take-back so as to melt the ABS goodie in the end of life to produce AM filament.

At this point of the session, a discussion was made about the possibility to use the EBM process, after an example given by the Env. expert of a bottle opener with a grid structure also used as a keychain. The AM expert explained that the EBM process would be very expensive and *over-grading* the product, thus not relevant for the manufacturing of a gadget such as the goodie. The Env. expert explained that the EBM process would provide a high environmental impact because of the high technical function delivered (metallic material) that could not fit to the functional expectation of the goodie (opening bottles vs. simple key protection). Thus, the AM expert proposed to use either SLM/SLS, which might also have similar energy consumption. However, the Industrial Designer raised the issue of the need for more support in manufacturing grid structures, which would yield in more waste and which would require more post processing operations. The Env. expert explained that it is more environmentally friendly to produce a more complex product with AM exploiting its full capabilities, rather than produce a simple product that is already manufactured in mass volumes in the industry with less environmental impact (related to the goodie functional unit). The Mechanical Engineer proposed to exploit the opportunity of AM to provide very thin and complex structures.

This discussion brought the participants to the proposal of a third idea, a cup holder. The Env. expert proposed to use a grid structure in order to use less material. The AM expert proposed to use stereolithography, and agreed that FDM or Polyjet processes could also be used as the product would be manufactured with a plastic material. For reasons of food safety, the participants concluded that PLA could not be used, and ABS was chosen. The Industrial designer suggested that the cup holder could be reusable and personalized and therefore would be a good choice for a goodie.

During the evaluation phase of the three ideas produced, the participants used the SWOT analysis. The SWOT analysis helped the participants identify the best idea among the produced ones giving emphasis on the environmental parameters.

Four of the participants chose the bookmarker as the best idea, however the AM expert voted for the key protection as the best idea, as it would exploit the capabilities of AM in a better way.

Table 3 AM materials table (extract), retrieved from CES Edupack software (Granta Design)

Material	Embodied energy, primary production (MJ/kg)	CO_2 footprint, primary production (kg/kg)	Water usage, primary production (l/kg)	Embodied energy, recycling (MJ/kg)	CO_2 footprint, recycling (kg/kg)	Recycle fraction in current supply (%)	Recycle	Downcycle	Combust for energy recovery	Landfill	Biodegrad
Metal (Aluminum alloy)	190–209	12.3–13.6	1.14e3–1.26e3	32.3–35.7	2.54–2.8	52.3–57.8	True	True	False	True	False
Polymer (ABS extrusion)	90.6–99.9	3.45–3.81	167–185	30.7–34	1.17–1.29	3.8–4.2	True	True	True	True	False

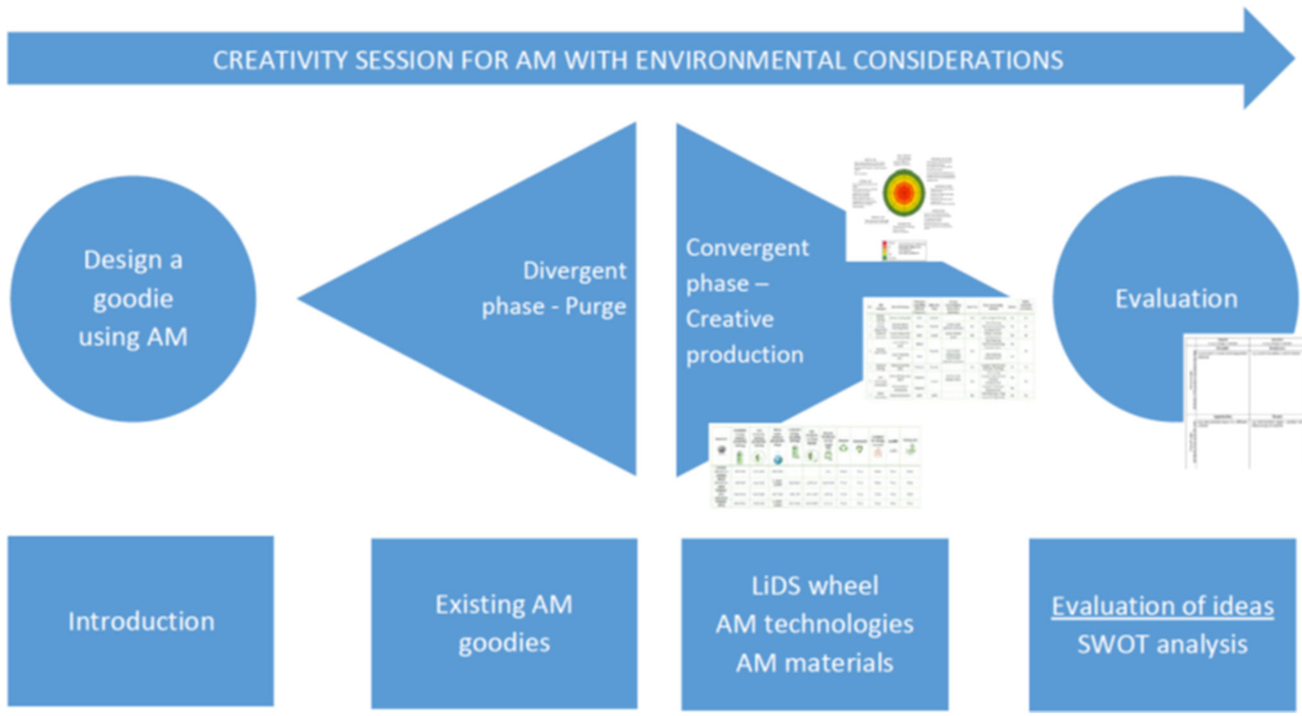

Fig. 2 Integration of the proposed method in a creativity session

4 Results

4.1 Participants' interviews

The participants agreed in general that the goal of the session was clear and well understood. However, they needed more input as to the purpose of the study and the way the results were going to be used. The ergonomics expert mentioned that the level of information provided might be too high for non-experts in AM or environment. The Mechanical Engineer expressed the need for more information about the end user, the amount of products that needed to be manufactured, and a comparison to conventional manufacturing processes.

The participants generally agreed that the information about the AM materials and processes was enough (Fig. 4), but different opinions were expressed as to the time the information should be provided.

According to the Mechanical Engineer, this information should be provided one or two days before the creativity session, while the Ergonomics expert founded that providing

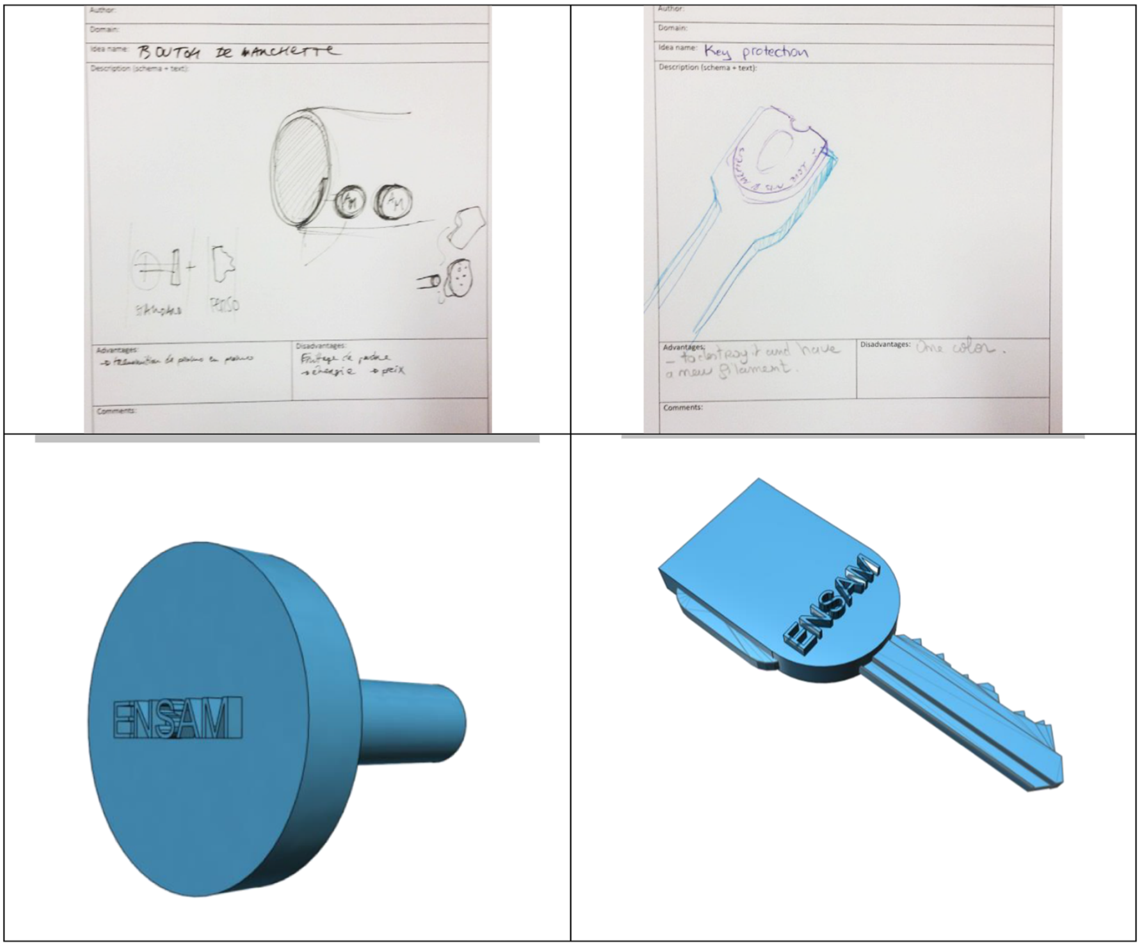

Fig. 3 Cufflink (*1st session, left*) and Key protection (*2nd session, right*) as examples of creativity sessions deliverables

this information before the purge stage (4) would not allow the participants to diverge.

The AM expert explained that the tools were a bit complicated for non AM experts and suggested that fewer AM processes information would be sufficient. In addition, the use of videos for AM processes rather than pictures and text would enable non AM experts to understand the AM processes.

Concerning the environmental parameters, even though the participants understood the information provided, they expressed the need for other information as well (Fig. 5). For example, the Mechanical Engineer needed information about the necessary time for biodegradation as well as the percentage of reusability of the material.

The Industrial designer expressed the need for information in the form of pictures including key numbers about environmental parameters. The Industrial designer also proposed the idea sheets to be adapted to the lifecycle stage (LCS) by transferring the LCS schema to the idea sheet, which would allow the participants to explain each concept in each stage. The Ergonomics expert preferred the information to be provided after the Purge (4) as expressed in the previous answers.

The participant knowledge about environment and AM technologies was minimum when it was not in their area of expertise. This hindered some of them from participating since the session focused on the integration of environmental considerations in the design process.

The participants provided input as to the issues concerning the organization of the session. As in the first session, the participants underlined the fact that the participation via visio-conferencing or other online systems hinders the interaction among the participants. The Mechanical Engineer proposed to devote more time to each phase in order to be able to develop the ideas to a more advanced level. The AM expert requested more visual tools to improve stimulation of the imagination. The Env. Expert needed to understand more the purpose of the study and the specific need for each expert, why their input is important for the session.

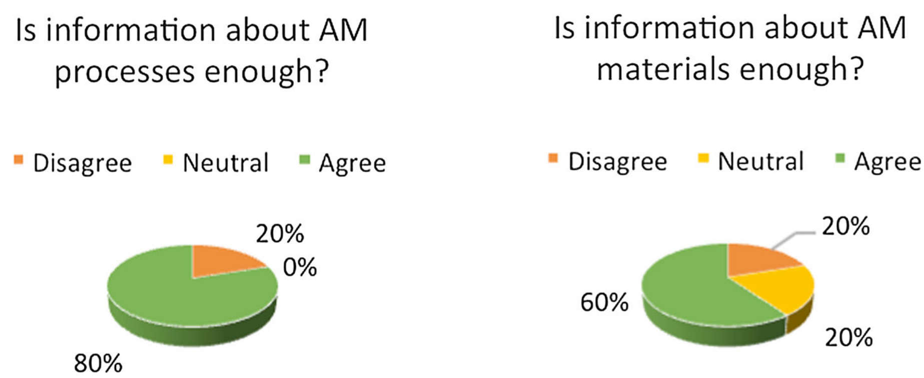

Fig. 4 Interviews results on AM information

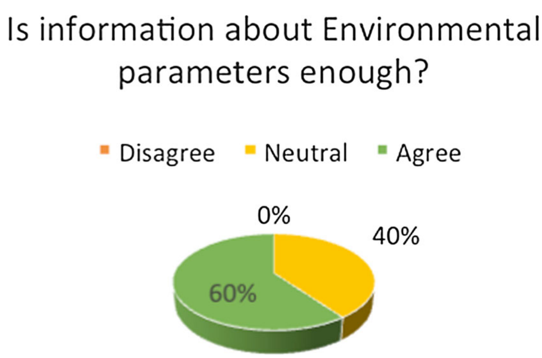

Fig. 5 Interviews results on environmental information

4.2 AM and Env./LCA experts' evaluations

According to the AM expert, the method supports the participants in making decisions both for the AM process and the material. Especially for the first concept during the second creativity session (the bookmarker) the use of paper material would be clearly linked to the product's function. In addition, during the first creativity session, the material considerations were limited, while the end-of-life of the material was not considered. The AM expert agreed that the products of the second creativity session were more suitable in terms of durability. The expert suggests that the participants were able to propose a more innovative solution in environmental terms in only one idea, the key protection, in which they proposed to melt the material in the product's end of life and reuse it in a new AM process.

The AM expert attested that the participants were able to choose the most suitable AM processes for the respective products. The expert also expressed strong agreement to the fact that the proposed tools and especially the SWOT analysis were useful to help the participants consider the energy and material consumption of the AM process. However, the expert added that the tool list given was not exhaustive and would require upgrading.

The AM expert considered that the lifecycle stages had been considered with this method on a global level. Additional time would be required for studying each lifecycle stage.

The AM expert proposed to include "defect parts" in the creativity session, which would indicate design errors that the participants should avoid and reduce time and printing errors. This would also help in reducing the environmental impact of the process, by decreasing the amount of generated waste. Thus, defect cards and parts should be included in the session, coupled with sustainability constraints.

The Env. expert explained that in the case of eco-design the material choice and the function of the product are connected. According to the expert this occurs in the second session, while in the first these are disconnected thus implying that the method encouraged the participants to make environmental decisions. In addition, in the second session the participants put a lot of consideration as to the end-of-life of the goodie, as opposed to the first session in which such considerations were limited. The SWOT analysis used in the second creativity session, was particularly helpful for the participants to raise the question of usage and end-of-life.

The Env. expert strongly agreed that the tools provided supported the participants towards making more environmentally friendly decisions. The expert suggested that the most important tools are the LiDs wheel and the SWOT analysis and proposed to include the choice of AM process in the SWOT. The expert explained that the SWOT enabled the participants to make environmental assessments easier because a support (the SWOT) was provided to capitalize information about the concepts that had emerged during the sessions.

4.3 Method improvement

Based on the feedback from the participants of the two creativity sessions and the experts' answers to questionnaires, improvements to the method can be proposed. The first proposition seeks to reinforce the lifecycle stage consideration of the product under development. As discussed

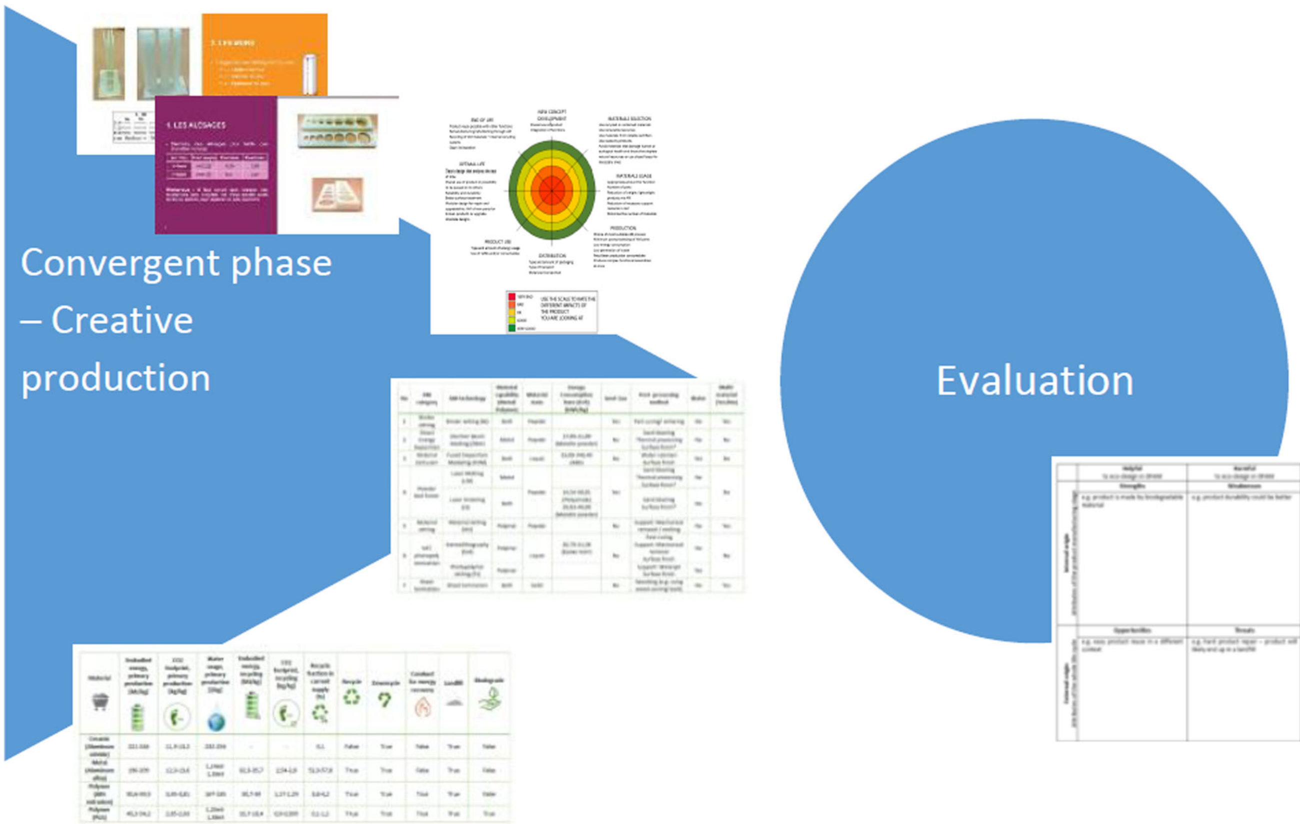

Fig. 6 Convergent phase in creativity session with environmental consideration and support tools

previously, when considering the environmental parameters of the product, it is of high importance to consider all the product lifecycle stages. This experiment showed the participants and the experts both acknowledge that the method needs to support the participants in making decisions for each stage. This was identified as early on as in the first creativity session, when the industrial designer proposed to center the creativity session not around the typology of the product but on its lifecycle stages. Therefore, two tools were provided to the participants, namely the table showing the lifecycle stages and the LiDS wheel. While these tools proved to be useful for the participants, their use could be improved by integrating them in the Idea Sheets to support participants formalize their decisions.

The second proposition concerns the improvement of the method in regards to DWAM. Specifically, the creativity session could include "defect cards", namely examples of AM design errors. Using these cards, the participants would be able to build on previously gained knowledge about AM and avoid the identified problematic designs. This would contribute to sustainable AM design, by minimizing trials and errors and therefore minimizing the produced waste.

Figure 6 summarize the convergent phase of the final proposed method.

5 Discussion

As observed in this research a multidisciplinary design team needs support in EDS to make decisions about the environmental performance of the product under definition. It is difficult to determine the major environmental burden that will be caused by a product at his EDS (concept definition stage). A small amount of information available also provides a lot of freedom to make environmental decisions on the design process. In addition, the specific characteristics of the AM processes and the DWAM methods need to be taken into account so that successful environmental integration can occur in the EDS.

The two experiments that were carried out underlined the importance of the right tool for supporting environmental decisions in creativity sessions (in industry). In these sessions, experts with diverse backgrounds and possessing little knowledge about the environmental aspects collaborated to reduce the potential environmental burden that would be caused during the product lifecycle. The experiments highlighted specific environmental information to provide at the right time during creativity cessions. The most important results of the experimentation highlighted the need to guide the experts to make decisions for each lifecycle stage of the product, as well as to bring specific information to participants about the possible additive manufacturing technologies, and with their associate energy and material flows. On the other hand, it is of equal importance not to provide overly explicit information to the participants that might stifle their creativity and imagination.

6 Conclusion

This research proposed a method for a first environmental integration during the Early Design Stage in a Design With Additive Manufacturing framework. The method combine the eco-design LiDs Wheel, information cards and material environmental impact results linked to a selection of the most common additive manufacturing technologies and a SWOT framework (Strength, Weakness, Opportunity and Treats). Based on two experiments the method came up with those four tools to effectively help multidisciplinary experts in envisaging the environmental performance of the emerging concepts around a collective definition of its functions, and potential performances during its lifecycle stages.

The method has been tested by the participants of the creativity session, their input, as well as the input of external experts, are taken into account to furthermore improve designing environmentally conscious products based on promising additive manufacturing technologies for the future.

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