A methodology to promote Circular Economy in Design by Additive Manufacturing

Simona Ianniello[1,2], Giulia Bruno[2], Paolo Chiabert[2],
Fabrice Mantelet[1], Frédéric Segonds[1].

[1] Laboratoire de Conception de Produits et Innovation LCPI – Arts et Métiers Institute of Technology – HESAM University,151 Boulevard de l'Hôpital, 75013 Paris, France
[2] Politecnico di Torino - Department of Management and Production Engineering - Corso Duca degli Abruzzi 24, 10129 Torino, Italy
simona.ianniello99@gmail.com

Abstract.

[Context] Within the framework of PLM; Circular Economy (CE) is an important concept that seeks to design out waste and pollution, keep products and materials in use and regenerate natural systems. Early Design Stages (EDS) are crucial because they set the foundation for the rest of the production process and can determine the product's overall functionality, usability, and manufacturing processes.

[Problem] As companies increasingly recognize the benefits of transitioning to a circular economy, there is a growing need for tools and methodologies to support the design of circular products and services.

[Proposal] This paper presents a CE card deck as a novel approach to facilitate the early stages of product development. The deck consists of 10 cards based on Morseletto's "Targets for a circular economy" work that represents mainstream circular economy principles and strategies and can be used by designers, engineers, and other stakeholders to generate ideas, evaluate options, and make informed decisions.

The results of a pilot study with design and engineering students (Master level) suggest that the card deck can support the exploration of CE concepts and facilitate the identification of circular solutions, in a Design by AM context (DbAM). The paper concludes with a discussion of the potential benefits and limitations of the card deck approach, and its integration into a PLM framework, and gives suggestions for future research.

Keywords: Circular Economy, Eco-design, Green Manufacturing, Environmental Impact, Life cycle engineering, Design by Additive Manufacturing

1 Introduction

In recent years, Circular Economy (CE) has gained significant traction as a solution to many environmental and economic challenges, by applying the reuse, recycling, and remanufacturing principles, with the aim of reducing waste and keeping products and materials in use for a longer period before they are discarded [1]. Product Lifecycle Management (PLM) should serve as a major help for companies looking to switch to a circular mode, by supporting them in the design and develop products more easily recyclable and repairable, thus with a longer life span [2]. Despite the crucial importance that CE will have in the coming years, there is a lack of tools to facilitate its application in the design phases of product development. In addition, researchers find promising the use of Additive Manufacturing (AM) in supporting CE strategies (e.g., providing recycled materials, repairing, remanufacturing, and recycling materials) [3]. For this reason, we have deeper analyzed the link between these principles as both, in the context of PLM, can help companies to stay competitive, adapt to the increasing demand for sustainable products, save costs, and improve environmental performance [4]. The Design by AM (DbAM) methodology prioritizes the integration of AM processes into Early Design Stages (EDS) to drive innovation. The concept generation phase provides an opportunity to fully utilize the distinctive capabilities of AM processes to create innovative solutions [5].

The research objective of this paper is to propose and validate in the context of DbAM a Circular Economy Card Deck as a tool that helps designers, engineers, and other stakeholders to generate ideas, evaluate options, and make informed decisions. Furthermore, a thorough examination of the strong connection between AM and CE has been conducted, including a detailed analysis of the opportunities provided by AM specific methods that assist designers in navigating the technical challenges of AM and how it aligns with CE principles [6].

The paper is structured as follows, section 2 presents a literature review on the CE, the obstacles associated with implementing CE in product design, and the relationship between CE and AM. Section 3 gives an overview of the research design approach. Section 4 presents the results. Finally, section 5 draws conclusions and presents future works.

2 State of the art

2.1 Circular Economy vs Linear Economy

Circular Economy is a broad concept, and more than one hundred definitions, offering multiple, sometimes contradictory, ways of conceptualizing CE have been identified [7]. What emerges from the literature review is the urgent necessity to transition from a Linear Economy (LE) to a Circular one, moving away from a resource consumption and waste generation model, towards a more sustainable and efficient system of resource use [8].
Sauvé et al. put forward a definition of CE that differs from the traditional linear economy approach. They argued that while sustainable development in the linear model primarily concentrates on minimizing waste, recycling, and pollution, the CE model places a greater emphasis on resources and considers all inputs and outputs of the production process, with a specific focus on waste management [9].

To provide and develop a framework of strategies to guide designers and business strategists in the move from a linear to a CE, the terminology of slowing, closing, and narrowing resource loops must be introduced [1]. These concepts are useful in the transition to a CE reducing the demand for new resources and minimizing waste.

1. Slowing resource loops: the utilization period of products is extended and/or intensified, resulting in a slowdown of the flow of resources.
2. Closing resource loops refers to the practice of recycling and reusing materials, rather than discarding them.
3. Resource efficiency, also known as narrowing resource flows, refers to the practice of using fewer resources to produce a given product or service.

Furthermore, to switch from a linear to a CE, the R-strategies [10] are very significant as they define a system in which multiple options and targets can be applied to promote CE implementation. The 10 Rs [10] are a set of strategies that can be used to promote sustainability and reduce waste by encouraging resource conservation and reuse.

Potting et al. [11] developed a framework that categorizes strategies for achieving circularity in order of increasing power, with R9 being the most powerful and R0 being the least powerful. This hierarchy should not be considered a strict rule, as there may be exceptions and secondary effects that can affect the effectiveness of these strategies, the hierarchy must be considered with caution and used as a general guide when evaluating CE strategies. As shown in fig. 1, R0, R1, and R2 strategies decrease the utilization of natural resources and materials applied in a product chain by fewer products being needed for delivering the same function. These three strategies are related to the Design Phase, strategies from R3 to R7 are related to consumption aspects of the products, and the latter two (Recycle and Recovery) are related to how to return the product after its life cycle came to an end.

CE

Smarter product use and manufacture	**R0**	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	**R3**	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded products or its part in a new product with a different function
Useful application of materials	**R8**	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recovery	Incineration of material with energy recovery

LE

Fig 1. CE strategies adapted from Morseletto et al. [10]

2.2 Challenges for promoting CE in the Early Design Stage

The EDS encompasses "project definition and planning," research and validation of the concept, and architectural design up to the preliminary layout creation [12]. In terms of production stages, one of the hurdles that CE faces is that it is usually more expensive to manufacture a durable long-lasting good than an equivalent quick and disposable version. This is a public good problem: the benefits of producing less or non-durable goods are private while the environmental cost is public [9].

Manufacturing companies need to prioritize sustainability to stay competitive in the market. One approach they can take is eco-design, which is the process of designing products with the goal of reducing their environmental impact throughout their entire lifecycle. This approach can be used as a strategy to improve the sustainability of a product during the early design phase [13]. Design for CE has recently come into focus as a new research area in the wider field of sustainable design [14]. Product life extension and complete recovery of products and materials form essential elements of this approach, design for a CE highlights the importance of high-value and high-quality material cycles [15]. An emergent field, in addition, is the potential contribution of AM to these circular strategies [16]. In fact, AM technologies are widely used in concept development [17] and could represent an important instrument for enhancing CE during the EDS of product development. Moreover, what emerges from the literature review is the “lack of environmental and lifecycle considerations in the curriculum for the Early Design Stages” [18]. Designers are facing a challenge in finding appropriate approaches for incorporating AM into the early design phases [19]. To assist designers in reducing the environmental impact of AM, two methods have been proposed. The first method is involving experts in AM during the EDS. The second method is providing designers with tools specifically designed for their work. These methods can also be applied to other areas beyond AM [20].

Within the context of DbAM, a useful supporting tool for inspiring the application of AM in product design is described by Lang et al. [6]. The authors defined 14 opportunities of the potential of AM (Topology optimization, material choices, multimaterials, monoblock…) and represented them in 14 inspirational objects, each associated with one opportunity, later shown. They proved that such methodology can help foster innovative ideas through associations between product sector-specific knowledge and the potential of AM [6]. The tool helps designers capture the design potential of AM to design creative solutions at the EDS by incorporating AM knowledge as early as possible during the ideation phase. The 14 opportunities of AM include shape complexity, hierarchical complexity, functional complexity, and material complexity, each with its own specific characteristics, such as freeform shapes, monoblock, material choices, and multi-materials. These 14 objects have been used in this work and have been implemented in the tool proposed for empowering CE, as better described in the next section.

2.3 Synthesis

In summary, we notice the necessity to transition from a linear economy to a CE in the field of product development. However, the implementation of CE principles during the design phase of product development is currently limited by a lack of tools and a lack of research. Additionally, there is a necessity to conduct further research on the intersection of CE and AM to fully understand the potential of these technologies to work together for sustainable production. These limitations highlight the need for further development of tools and deeper research in this area to fully realize the benefits of CE in product development. We can conclude there is a lack of methodology to support CE in the EDS/AM frameworks.

3 Research design approach

The methodology incorporates a card deck and 14 AM opportunities to assist designers in integrating CE principles and maximizing the opportunities for AM during the EDS. After that the experiment has been conducted, participants have been asked to evaluate the tool proposed.

3.1 Circular Economy Deck tool

This study proposes a Card Deck tool, named “Circular Economy Deck”, as cards are valuable for “sparking creativity, externalizing tacit concepts, constructing and organizing ideas, and working both playfully and collaboratively" [21]. Collaborative and open strategies for EDS have been demonstrated as crucial tools for the implementation of successful CE [22]. This tool can help designers to analyze, ideate, and develop the circularity potential in their projects during the EDS of production. The tool is based on the previous literature review of circular-oriented innovation principles and strategies to realize it. The principles are organized according to the intended circular strategy outcome that they pursue (narrow, slow, close, regenerate) [23], and one of the 10-R strategies [10] that each card is representing.

Fig. 2 shows the Circular Economy Deck. Each of the 10 cards represents a CE strategy on which it is important to be focused. On the back side of the cards, the explanation of the strategy is presented with a user-friendly image, and on the front side a score and the strategic effect between slow, narrow, close, and regenerate is assigned. A legend card is provided with the 10 cards in the deck as well. In each card, each strategy's effects in terms of Life Cycle Assessment have been explained thanks to the symbols under the title. To decide the existing link between each strategy and each of the 4 symbols present or not on the card, an analysis with 3 experts on the CE framework has been conducted.

Fig. 2. Circular Economy Deck is composed of 10 cards and 1 legend card front and back sides.

3.2 Experiment for tool exploitation

The experiment was conducted with 12 master's engineering students. The objectives of this experiment are to evaluate the effects of using the Circular Economy Deck during the EDS of a product and to deepen the relationship between CE and AM. To reach this goal, 5 phases have been conducted involving creativity, CE information, and AM knowledge.

Table 1. Phases of the experiment

	Phase 1: Introduction to Additive Manufacturing processes	Phase 2: Introduction to Circular Economy concepts	Phase 3: Presentation of the Card Deck for Circularity and of the AM Cubes	Phase 4: Creativity session "*The foldable helmet of the future*"	Phase 5: Questionnaires
Group using Card Deck	5'	15'	15'	125'	10'
Group without Card Deck				125'	10'

Table 1 describes the approach used for evaluating the Cards-based tool.

5 phases composed this approach:

- 1st phase: Students are introduced to AM Processes through a presentation with PowerPoint.
- 2nd phase: Students are introduced to CE concepts through a presentation with PowerPoint.
- 3rd phase: Present and explain each card of the Circular Economy Deck to the students. Students have also used the AM opportunities [21].
- 4th phase: Creativity session: twelve students were separated into 2 groups. 6 students from the 1st group used the Circular Economy Deck for generating their idea sheet and 6 students, from group 2, did not use it. Both groups have used the 14 AM opportunities cubes. The teacher in charge of the creativity session presents the brief: "design the foldable helmet of the future".
- 5th phase: After having realized a creativity session using brainstorming, purge phase, and inversion phase to offer a maximum of Idea Sheets (IS), students have been asked to fill in different questionnaires.

During the 1st and 2nd phases, a short lesson about AM and CE has been provided to the students to briefly explain these concepts. In the 3rd phase, students have been introduced to the Circular Economy Deck and an explanation of how to use the cards is rendered. The 4th phase is shown in fig. 3, representing how the Creativity session has been conducted.

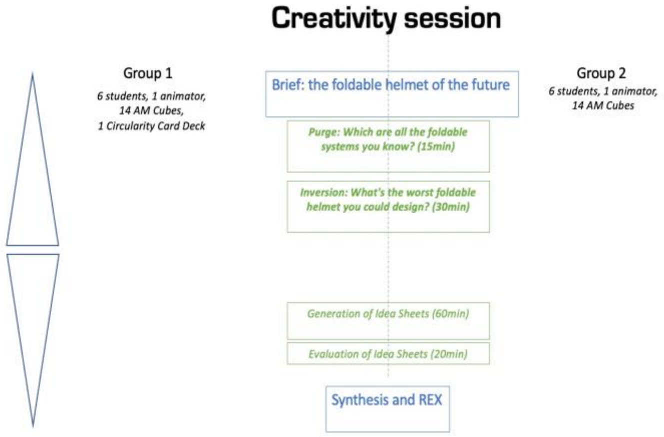

Fig. 3. Structure of the Creativity Session in the 4th phase has been conducted.

3.3 Evaluation of the tool

During the 5th phase, different questionnaires were proposed to all participants to assess their feelings about this approach. Five questions, reported in Table 2, were asked to understand participants' interests, their perceived acquisition of CE knowledge and the application of these concepts for developing the idea, and their perceived acquisition of CE knowledge related to AM processes. In addition, students who used the Card Deck must declare which cards have been used in the development of their idea.

Table 2. List of questions to the participants

List of questions
1. I feel more able to explain the main concepts of CE.
2. I think that I have better understood the relationship between CE and AM.
3. I feel capable of proposing ideas of the innovative object being more focused on the opportunities of the CE.
4. I feel able to explain and exploit all the pursuable strategies for Circularity.
5. I think I have mastered the CE strategies and their power.

Students have been asked to complete a matrix shown in table 3 for evaluating the relationship between each of the 14 AM cubes and the CE strategies presented in the cards. We asked the students to rank the top 3 CE strategies more powerful for each cube and more related to each opportunity the AM cubes want to refer to.

Table 3. Matrix to fill in to rank the relationship between CE strategies and AM opportunities. Each cube is different from the others and represents one AM opportunity. This matrix has been used to evaluate how much each opportunity is impactful on CE strategies.

AM CUBES / CE STRATEGIES	1	2	3	4	5	6	7	8	9	10	11	12	13	14
REFUSE														
RETHINK														
REDUCE														
REUSE														
REPAIR														
REFURBISH														
REMANUFACTURE														
REPURPOSE														
RECYCLE														
RECOVERY														

1. Segmentation
2. Embedded components
3. Internal channels
4. Infilling
5. Auxetics structure
6. Material choices
7. Multi-materials
8. Freeform shapes
9. An object from 3D scans
10. Microstructure variation
11. Texture
12. Monoblock
13. Topology optimization
14. Non-assembled mechanisms

4 Results

In total, 8 Idea Sheets (IS) were generated. 1st group, that used the card deck, realized 4 IS and 2nd group realized 4 Ideas Sheets as well. Fig. 4 presents an example of one of them. It is a new concept of a foldable bike helmet as the Creativity Session theme was "*The foldable helmet of the future*". In fig. 4, the innovative helmet is thin and retractable, when it is closed it looks like a headband and it unfolds as painted protecting the head and spine. The materials involved in the production are entirely recycled.

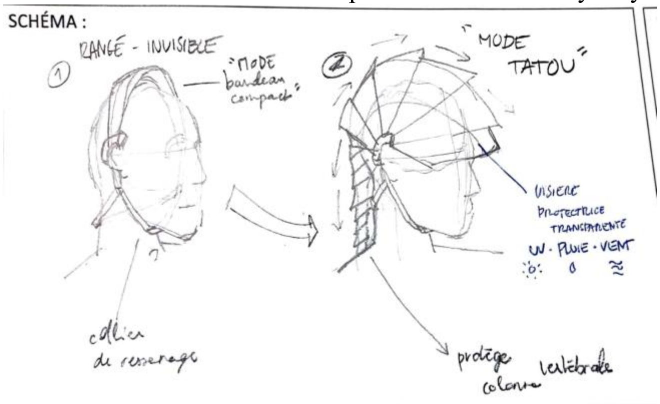

Fig. 4. Example of a spontaneous generation of an idea for the "Foldable helmet of the future".

4.1 Results on Circularity Level

Participants have been asked to declare which cards they used for developing the Idea Sheet and the results, shown in Table 4, reveal that the most used strategies are Reuse, Repair, and Recycle. These 3 cards have been used for each idea generated with the Card Deck. The average of cards used by the students is 4 cards for each Idea Sheet created, this result is a good clue to declare that the tool helps designers in being focused on circularity's aspects during the EDS.

Table 4. Table counting how many times each card has been used by participants with the Card Deck.

Card	Number of uses
REUSE	5
REPAIR	5
RECYCLE	5
REDUCE	4
REFURBISH	4
REMANUFACTURE	4
RETHINK	3
REPURPOSE	3
RECOVERY	2
REFUSE	1

4.2 Results on the feeling of CE performance

Students have been asked to answer the following questions, also presented in table 2., choosing their answer on a scale of agreement. The answers permitted were "Totally Disagree", "Disagree", "Somewhat Disagree", "Somewhat Agree", "Agree", and "Totally agree" and they have been transposed to a scale from 1 to 6.

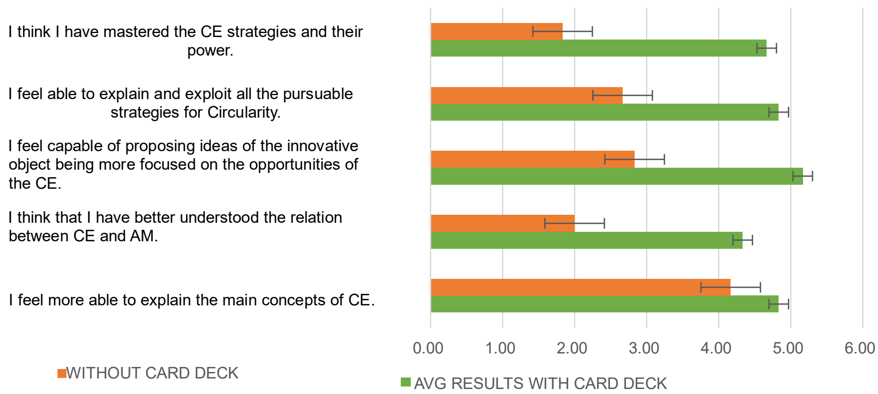

Fig. 6. Results of the satisfaction questionnaire (6 students per panel).

The results of this questionnaire indicate a better understanding of the CE strategies among the group of students who utilized the Circular Economy Deck. This is confirmed by the students themselves, who reported feeling more able to explain and apply the strategies related to CE. Additionally, those who used the Card Deck stated that they felt more capable of proposing ideas for innovative products, with a greater focus on CE opportunities – which aligns with the tool's intended purpose. Furthermore, the students reported that the relationship between CE and AM was clarified and better understood with the tool provided. To further confirm the effectiveness of the research approach, it has been asked to the students if they felt more able to explain the main concepts of CE. The results of this question show that the gap between the two groups is not as significant as for the other questions even if present, suggesting that Phase 2 of the research was useful and confirming the previous results. Overall, the students' positive feedback and a better understanding of CE strategies using Circular Economy Deck provide valuable insights into the field of PLM.

4.3 Results on the link between AM and CE

The results of this table confirm and empower the strong link already studied between AM and CE strategies. Participants were asked to rank the top 3 strategies most powerful for each cube and more related to each AM opportunity. Table 5 represents the correlation between each strategy and each cube because of the data collected after counting the times each strategy has been declared in correlation with the others from the data collected in table 3. The red cells are those characterized by a low level of correlation between the strategies and the AM opportunities, this is also represented by values from 0 (lowest) to 10 (highest) grades of correlation.
The AM opportunities with the highest number of strategies associated are non-assembled mechanisms, material choices, segmentation, and objects from 3D scans. The strategies that resulted in being the most related to AM processes are Rethink, Reduce, Recovery, and Reuse. In contrast, the AM opportunities that are less related to CE strategies are multi-materials, embedded components, and infilling.

Table 5. Table showing the relationship between AM opportunities and CE strategies.

	Non assembled mechanisms	Material Choices	Segmentation	Objects from 3D scans	Texture	Topology optimization	Internal Channels	Microstructure variation	Monoblock	Freeform shapes	Infilling	Auxetics structure	Embedded components	Multi-materials
RETHINK	8	3	4	8	0	5	6	2	1	1	6	3	2	4
REFURBISH	5	10	2	1	7	2	0	0	0	6	2	0	1	3
REPURPOSE	6	2	2	1	6	0	1	1	3	0	3	2	4	2
RECOVERY	3	4	3	0	10	3	0	5	5	1	0	3	5	2
REPAIR	4	5	8	6	0	2	4	0	0	0	0	0	0	1
REDUCE	3	4	0	5	7	8	7	1	2	3	5	7	0	0
REUSE	6	6	6	1	0	0	3	3	3	5	3	1	3	0
RECYCLE	6	3	3	6	2	0	4	5	6	0	1	0	0	0
REFUSE	3	1	3	8	2	4	2	6	3	4	0	4	0	0
REMANUFACTURE	3	2	10	1	0	5	0	2	0	3	0	0	2	0

4.4 Synthesis of results

The results of a survey on the usage of the Circular Economy Deck tool among students indicate a better understanding and application of CE strategies. The students reported feeling more capable of proposing innovative products with a focus on CE opportunities, and the relationship between CE and AM was clarified. The top three CE strategies identified by the students were Reuse, Repair, and Recycle. The AM opportunities with the highest correlation to CE strategies were non-assembled mechanisms, material choices, segmentation, and objects from 3D scans, while multi materials, embedded components, and infilling were less related. Overall, the results confirm the strong link between AM and CE strategies, the effectiveness of the research approach to empower circular aspects during the EDS of production and the students provided positive feedback on the tool.

5 Conclusions and Future Work

The main research focus of this paper is discovering if the most important concepts related to CE can be learned and kept in consideration during the Early Design Stage of Product Development thanks to a Circular Economy Deck that aims at increasing awareness of CE concepts during the EDS of production, in a Design by AM context. The study involves 3 domains: creativity, CE, and AM. The results of a pilot study with master's design and engineering students suggest that the Circular Economy Deck can support the exploration of CE concepts and facilitate the ideation of eco-products. Moreover, by introducing concepts and tools related to AM during the testing phase, the study improved understanding and awareness of AM's potential applications in the CE field.

One of the limitations of this work is the number of students involved in it. Future research is vital to continuously update the tool with new strategies, and, more generally, to try to test the tool first with more groups of engineering students and then in companies. Later, it would be interesting to assess the cards by industrial experts in the domain. Furthermore, there is value for future research to develop sector-specific versions of this Circular Economy Deck such as for Industry 5.0, biotech firms, green buildings and constructions, sustainable agriculture and food systems, and similar companies.

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