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"From Abstractness to Concreteness – experiential knowledge and the role of prototypes in design research"

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Conference Proceedings

From Abstractness to Concreteness – experiential knowledge and the role of prototypes in design research

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Conference theme

Prototype and prototyping play a key role in experiential knowledge since they support the interconnections and collaboration among researchers and practitioners in many design fields. The role of prototypes in design research is characterised mainly by the general function of representing ideas and giving intelligible form to undetermined and abstract concepts pertaining to design solutions. Such a principle of transition from vagueness to clarity illustrates views on the role of prototypes which dot the diverse landscape of design research. Indeed, the evolution of design research in the past twenty years has led the path to a wide range of new possible prototypes applications.

Originally, in the industrial context, prototypes were made to test, evaluate, and improve the product until the final design and production phase. When design became an academic discipline, the scope of its enquiry expanded, embracing new areas of interest (i.e., sustainable design, materials design, participatory design, service design, user experience design, etc.), and their methodologies and scopes. During this evolution, the role that prototypes play in design research started to be questioned.

Indeed, nowadays, the role of the prototype encompasses several possibilities that link to the context and aim of the design research. When a general aim of the investigation is to develop a new design solution and make it *real* and available to users at the end of the process, prototypes support the transition from the idea to the final product. In this realm, prototypes play a crucial role, as they visualise, validate, experiment, and create such new solutions. Interestingly, prototypes for this kind of design research can be simple paper models that anticipate interactions up to complete *working* prototypes that are very close to the final product. In the digital field, provisional solutions are released on the market and updated afterwards. Prototypes, in this case, merge with the *final* products. New boundaries are broken between a final design and what is not.

Furthermore, the products that designers call to envision are becoming more and more complex. They are equipped with sensors, processors, and connected devices that support the interaction with digital interfaces, applications, and complex services. Hence, prototypes are meant to support design processes that rely on the supplementation of new kinds of expertise – such as user experience design, interaction design, material design and computer science – besides those traditionally integrated – such as product design, mechanical and electronic engineering). In this regard, the prototype embodies the translation of different design languages into a developing concept. Moreover, design research that explores and discusses possibilities might go beyond the development of concrete solutions and tackle significant issues (i.e., the impact of technology on society; climate change, social innovation) to reach new understating and develop new knowledge. This kind of design research usually occurs in academia and requires exploratory and speculative studies. Some of this design research is about tangible objects or is based on material experimentations. Typically, prototypes play an important role in the first explorative phases, in this realm since they enable the transition *from abstract to concrete* through immediate and factual experience. Designers research by envisioning solutions, imagining possible futures, exploring new fields, and feeding the design discourse with emerging contemporary issues and fictional scenarios.

Overall, the multifaceted landscape of today's design research opens to a wide range of meanings that define what a prototype is and does. The discussion on prototypes' identity is open. Instead of seeking to find an ultimate definition of prototype and its role in today's design research, the conference aims at eliciting a conversation around the current and multiform panorama of experimentations around and with prototypes.

The call for paper encourages contributions with the following:

- What are the new roles of prototypes in these evolutionary pathways in design research?
- How do new sophisticated, integrated, and advanced prototypes support research in various areas of design?
- How do different research contexts (practice, R&D, and academia) collaborate in design research due to the making and use of prototypes?
- How do prototypes enable the creation of theoretical knowledge and support speculative research?
- How do prototypes enable the creation of practical knowledge and support empirical research?
- How do prototypes enable the exploration of new research fields?

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Exploring 3D Printing Strategies for Designers to Reach Circularity

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Abstract

Additive Manufacturing has been identified as a disruptive emerging technology and has great potential for sustainability and the implementation of the circular economy. However, to date, new generations of designers have tended to utilize it as a mere tool for the three-dimensional representation of a solution conceived and designed for other supply chains. This not only creates experiential and perceptual problems in relation to AM but actually represents a misuse of material resources, which are utilized in an uninformed manner.
With this in mind, the paper aims to chart possible directions and strategies to foster an informed use of AM within the Circular Design design and production process.
After an introductory framing of the current issues and peculiarities of AM, we present the five strategies identified to enhance the potential of 3D printing within the framework of the ecological transition. These strategies are the starting point for defining a roadmap to better understand and consciously use AM in the design of circular and sustainable solutions.

Additive Manufacturing; Study Model; 3D Printing; Circularity; Circular Design

The educational path related to Design as a discipline is composed of the transmission of a variety of knowledge, multidisciplinary and interdisciplinary, for the constitution of a professional skilled in both the conception and communication of solutions responding to the principles of innovation, ethics and usability towards third parties, such as clients, users, companies, etc. This ability is transmissible through multiple tools and techniques, among which the effectiveness of using study models as a design method (Polato, 1991) is outstanding.

According to the Project-Based Learning (PBL) approach (Kokotsaki et al., 2016; Newman, 2005), which is very important in Design, study models assume a major role in the design phase (Tonelli, 2008; Branzi, 2015), as they actually consist of the real moment of tangible understanding of the solution conceived in the mind, visualized on paper or on a screen, which has never been concretely experienced until that moment. In the same way that no one knows how to write without correcting (Nizzoli in Polato, 1991), the design process also requires that after an initial phase of formal definition of the envisioned concept, there are necessary moments of verification, which can be effectively achieved through the creation of study modelsIndeed, study models are artifacts made in the midst of the design phase as an active tool for verification and formal redefinition (Tonelli, 2008; De Fusco, 2008); what is relevant is not so much their aesthetic quality but their ability to be adherent and responsive to design needs (Polato, 1991). Their proper use, therefore, asseverates them to be an active tool in the iterative design process of refining an idea.

While in the early stages study models were traditionally handcrafted from cembran wood (Polato, 1991; Bettiol & Micelli, 2014) because it is easily machined and free of knots, to date such artifacts are mainly in other materials (paper, cardboard, polymers, foams, resins, etc.) and created partly by hand, partly through the use of digital fabrication machinery, such as CNC milling machines, laser cutting machines, and 3D printers.

This trend is a reflection of a growing attitude that leads design students to approach the ideational phase of the design journey by increasingly reducing the exploratory moment of ideas through sketches and immediate drawings on paper, preferring to move directly into a three-dimensional space, thanks to modeling software, which is increasingly popular and has intuitive interfaces. Thus, when the three-dimensional file replaces the sketch, the study model also undergoes a transformation in meaning and identity, becoming the product of a 3D printer.

This trend, which presents several issues from the point of view of theory and design practice, is steadily growing and very difficult to argue against, partly because of the rise of entry-level 3D printers (Jandyal et al. 2022; Wohlers et al., 2022), which are affordable and increasingly popular in schools and homes.

Unfortunately, when three-dimensionally printed artifacts take the place of the study model in the design phase, there are mainly negative effects, as students often self-limit themselves in devising formal and functional solutions that do not have as their only main purpose compliance with previously settled design requirements (Bolzan & Ascani, 2022; Ascani et al. 2022). Thus, the democratization of 3D printing technology (Aldrich, 2014; Von Hippel, 2005) in this specific setting means that the proposed design solutions come up against the level of knowledge acquired in the use of 3D modeling software, through which 3D printing files can be generated, which turn out to be limited and limiting, especially during the formative years of education. The same thing also tends to be reflected in the design practice of young professionals. Moreover, when 3D printers are used to shape an idea, they are rarely considered as a production technology, but rather a tool for direct materialization. In doing so, there is often a lack of understanding that objects designed for another production chain do not necessarily turn out to be correct when materialized with entry-level 3D printers, or Fused Deposition Modeling (FDM) and/or Fused Filament Fabrication (FFF) printers in general.

In observing the emergence and radicalization of this trend, therefore, we want to reflect on what might be a strategy not so much to combat it as to redirect it in a more functional way to design practice. From the premises given, it is argued how it is more interesting to maintain the dialogical and iterative dimension between the design and prototype phases, to be considered as an active moment of the design process. For this reason, thinking about Additive Manufacturing (AM) as both a design/prototypical and production tool can be a strategic element to raise an aware generation of designers, but also to try to find more sustainable applications of this technology. AM, in fact, should be considered not only as a family of manufacturing processes, but also as an enabling tool for the design workflow, with its own possibilities, limitations and peculiarities. Designing "for" and "through" AM means not only knowing its advantages, disadvantages, and principles of operation, but also questioning in an informed and conscious manner the circumstances and conditions under which it may make sense and sustainable (economically but especially environmentally) to employ this technology, which primarily uses polymeric or composite materials (leading to the generation of waste microplastics) and resins (requiring washing and curing processes with impactful chemicals).

This is why it makes sense to use AM responsibly and consciously, in a way that also fosters synergy between designers' responsibilities and the achievement of the Sustainable Development Goals (Chou, 2021). In the remainder of this contribution, we will proceed in framing how AM can foster the achievement of these goals once we truly understand the multitude of possibilities it offers, without relegating it to a tool for uncritical prototyping.

Additive Manufacturing as an enabler of Circular Design

The linear production model (Jiang, 2022), on which the industrialized production system is mainly based, although it has brought economic growth and prosperity, is no longer sustainable from the point of view of the planet's resource consumption (Sariatli, 2017). To ensure the implementation perspective of circularity, the Design is called to take on a mission of rethinking and redefining what should be the priorities when going to conceive, design, prototype, produce and use a product. Indeed, a design approach supporting linear production (Sariatli, 2017) traditionally focuses primarily on the product and how it is manufactured. In designing a new commodity, the impact of the product during its production and consumption is not addressed, nor is what happens after the product is no longer in use and is disposed of. But even before these stages, there is the design dimension that has relevant implications for the aspects of choosing the materials and technologies that should be used. For this reason, it’s quite urgent to make a change moving from design for Linear Economy to design for Circular Economy. Design in the Circular Economy is intrigue and requires a transformation in thinking, to shift 'from the current product-centric focus towards a more system-based design approach' (RSA, 2014). Circular Design seeks to produce a product or service that is useful and composed of the best materials to give the highest performance while reducing its overall negative impact (Aho, 2016).

AM technology represents an opportunity with benefits at both the product and system levels, and has a high potential to serve as a facilitator of the circular economy (Garmulewicz, et al, 2018), including the opportunity to better manage the resource consumption. There are two main features (Jimenez et al., 2019) of AM to leverage, because they not only provide significant competitive advantages but also reduce manufacturing costs:

- The geometrical complexity of the part can be easily manufactured based on the geometrical template obtained from a 3D CAD.
- The customization of the part can be simply manufactured, and products that are identical or wholly different can be obtained without affecting the process or expending additional costs.

These two characteristics of 3D printing can provide massive benefits in different applications: (1) Lightweight Products; (2) Multi-material Products; (3) Ergonomic Products; (4) Integrated Mechanisms. Referring to Lightweight Products, AM permits the production of items customized to a certain function and with customized characteristics. Some 3D printing processes can even fill a model with varying degrees of porosity without changing the material. When we consider Multi-material Products, AM enables the production of a product employing multiple materials in the same solid at the same time. This suggests that the technology overcomes one of the present weight/mechanical strength ratio constraints by introducing new functions or cutting manufacturing costs (Attaran, 2017). The components' design with AM for Ergonomic Products can provide a higher level of connection with the user by responding to the precise anthropometric features of each individual (i.e. prostheses) without necessarily influencing manufacturing costs. And lastly, AM offers the possibility of producing Integrated Mechanisms that are totally incorporated into the finished object, without the need for subsequent assembly and adjustment.

In terms of the manufacture of industrial components, the following benefits must be recognized as noticeable.

Reduction of the time it takes new designs to reach the market

When additive manufacturing is used as a manufacturing technique of the end product and not only in the production of prototypes, many of the current launch and validation phases can be drastically shortened. Another advantage is that it provides great flexibility when it comes to responding to the continuous changes in market demand.

Short production runs

The size of the production run con be minimal to the extent of being on a per unit basis while hardly influencing manufacturing costs (if and when the depreciation of the equipment is not considered). One of the characteristics that make this possible is the lack of a need for tooling, which represents a considerable advantage with respect to the conventional manufacturing methods.

Reduction of assembly errors and their associated costs

Ready assembled components can be obtained with the only subsequent operation being the quality control inspection.

Reduction of tool investment costs

Tools do not form port of the 3D printing process This represents a great deal of flexibility as regards adapting to the market and a reduction, or even elimination, of the associated costs (toolmaking, stoppages due to referred changes, maintenance, and inspection).

Hybrid processes

It’s always possible to combine different manufacturing processes In this case combining 3D printing processes with conventional processes might be interesting to make the most of the advantages offered by both.

Material consumption

Optimum usage of materials material wastage is reduced to a minimum. Any waste material can be easily recycled.

Five Design Strategies for Sustainably and Circularly using AM

In light of these considerations, and thanks in part to the great freedom in realization offered by AM, one could consider this technology as the answer to any design/manufacturing input. However, although almost any geometry can be realized through AM, it does not necessarily make sense or meet sustainability and circularity requirements when realized through the use of 3D printing technologies (Liu et al., 2016). Therefore, what are the motivations that may lead a designer to choose AM as a project and production strategy instead of other more widely used technologies?

Downstream of some observations conducted on the most effective experiences of using AM in the materialization of products, and based on previously developed experiences in prototyping in Fab Labs and research laboratories (Bolzan et al., 2021; Bianchini et al., 2019), 5 drivers were identified that can frame the correct motivations behind the use of AM in the design process: Attachment, Efficiency, Reparability, Recyclability, and Distributed Manufacturing.

Attachment

In Circular Product Design Strategies, Design for Attachment and Trust refers to the production of things that will be loved, appreciated, or trusted for a longer period of time to slow resource loops (Chapman, 2009). This is also known as "design for emotional durability": a scenario in which "people and goods thrive within longlasting empathic partnerships", it is a good method to extend product lifespan leveraging four main product meanings (Mugge et al., 2008): Self-expression, Group affiliation, Memories and Pleasure (or enjoyment).

Compared with traditional production technology, 3D Printing is very suitable for applying the strategy of implementing product personalization or making the product more unique to improve product attachment. The traditional process used to produce conventional parts and components is impacted by a series of limitations related to obtaining certain shapes, and if you want to make geometrically complex pieces, neither the mold will be very complicate nor can you get the component out of the mold tools. Thanks to 3D Printing's unique working principles, the geometrical complexity of the part can be easily manufactured based on the geometrical template obtained from a 3D CAD (Kondoh et al., 2017).

Another advantage 3D Printing brings is that the customization of the part can be simply manufactured for AM, products that are identical or wholly different can be obtained without affecting the process or expending additional costs, which means a great deal of reduction in tool investment costs. Besides, by responding to the precise anthropometric features of each individual also for medical products and prothesis, the personalization of parts is tailored to the individual needs and preferences of consumers without necessarily influencing manufacturing costs. 3D Printing makes it possible that designers, customers, and manufacturers to collaborate to create innovative products, this co-design process involves user participation in design, product simulation/certification, manufacturing, supply, and assembly processes that rapidly meet consumer needs and preferences Encouraging product attachment is valuable for a Circular Economy, it can result in product longevity, which is generally recognized as an important Circular Product Design Strategy Compared to the other strategies, strengthening the person-product relationship is that it does not require consumers' pro-environmental behavior. Once the emotional bond is built, a person will take better care of this product and postpone its replacement for his/her benefit. Infact, the strategy of increasing the product's reliability and durability to extend its lifetime is not always effective, because many products are still replaced while they are still functioning well at the end.

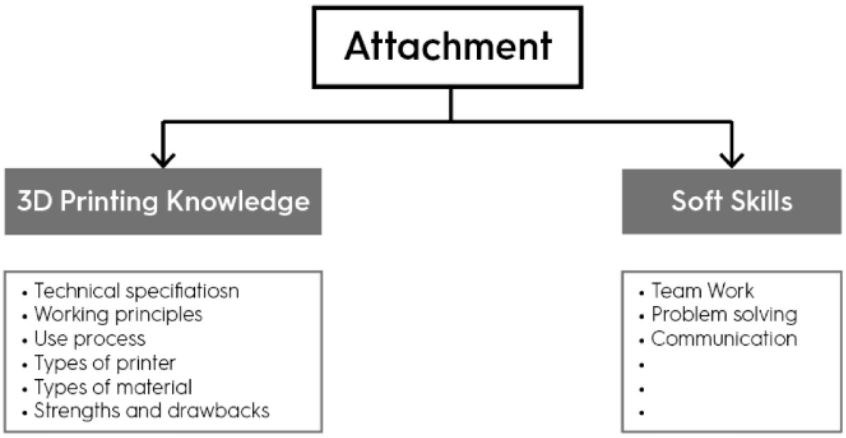

Figure 1: Attachment influence on designer.

Efficiency

AM allows the creation of complex geometries through its distinct working principles, which can lead to a reduction in material usage, part consolidation, simplified assembly lines, increased product functionality, and reduced energy consumption (Nagarajan et al, 2016). Meanwhile, the emergence of innovative generative design broadens the application bounds of 3D Printing, and 3D modelling softwares can quickly generate multiple design alternatives according to process, material, cost, and other parameter constraints, and designers can choose the best solution according to technical requirements (Wang et al., 2021). Through this automatic topology optimization a part can be optimized to a lighter and stronger structure/ yet the structure is usually too complicated and organic for traditional manufacturing methods to produce for AM the part can be easily manufactured (Rajan et al., 2022). We can conclude that AM is well suited to a lightweight design that saves energy.

The enhancement of resource efficiency can be separated into several categories.

Firstly the product development costs can be lowered by 3D Printing especially for the prototypes can be easily made to verify the design. Secondly, the low weight of the product through the optimized geometry saves the materials/ and waste materials are reduced to the minimum. Besides, the optimized geometry with enhanced structure and low weight will improve the product energy utilization performance. Thirdly, the emerging eco-design concept of Monomateriality which is building products from a single material, benefits a Circular Economy by dramatically simplifying the logistics and transaction costs of materials cycling (Chiaroni et al., 2021). Luckily, 3D printing, by its fundamental nature, inherently uses a Monomaterial to build up complex 3D forms.

In Circular Product Design Strategies, design for standardization and compatibility, and design for dis-and reassembly are preferred to recycling, as this help retain a product's economic and environmental value over time. While in this 3D Printing design strategy, creating complex yet optimized shapes encourages the designer to build a single part product that is easy to recycle and thus contributes to Circular Economy, it looks like that 3D Printing counters the traditional Circular Product Design Strategies, or if we think oppositely, Circular Product Design Strategies are enriched by 3D Printing, the complex yet mono material-built product can be recycled to become the raw material to create new designs.

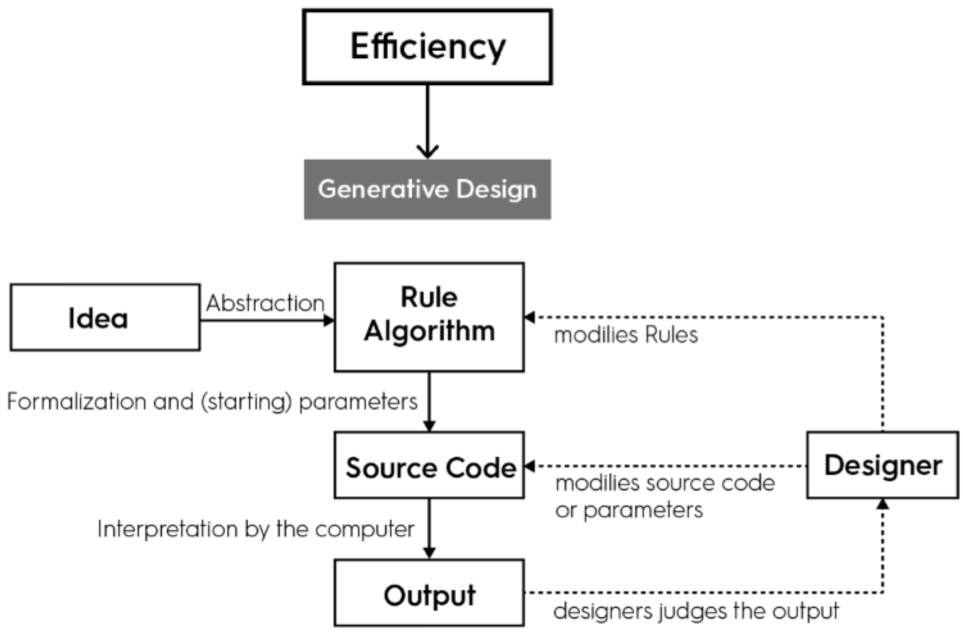

Figure 2: Efficiency influence on designer.

Reparability

Design for ease of maintenance and repair is one of the Circular Product Design Strategies, it aims at extending product life to slow resource loops. Repair is about restoring a product to a sound/ good condition after decay or damage, since 3D Printing is a way of digital production, it favors repair because broken parts can be imitated and reproduced.

For the products made by 3D Printing, the model file of the product is stored digitally and you can just produce them on demand (Mani et al., 2014), this reduces inventories and saves storage costs, making repair more accessible (Ford & Despeisse, 2016). The broken part can be replaced with the new printed one, and unlike the traditional manufacturing method, the size of the production of 3D Printing hardly influences manufacturing costs.

AM can also be very helpful for repair the products that are not originally made through a 3D printer. There are three different kinds of repair 3D printing can do. The first possibility is when the waste products can be turned into new daily necessities, the part made by 3D Printing adds new meaning to the waste and repurpose them. More easily, the damaged part can be replaced by the new 3D Printing part, besides the new part does not just fix the old product, but also add value to the new product resulted. Lastly, 3D Printing does not aim at repairing the original work, but to change the broken part into something with additional cultural/artistic value.

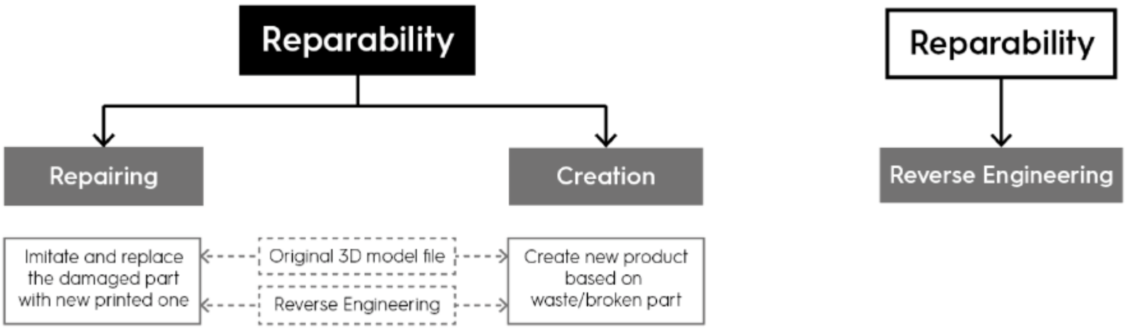

Figure 3: Reparability influence on designer.

Recyclability

For any manufacturing process, including 3D Printing, the feedstock must be formed into a state compatible with the process, and the material must exhibit acceptable service properties to perform successfully in the given application.

Materials play a dominant role in 3D Printing, particularly when considering materials for engineered structural applications. To be successful, materials must be formed into proper feedstock, have appropriate characteristics for processing in the specific 3D printer, and must have acceptable service properties (Bourell et al., 2017). So, it can be inferred that the recyclability of materials determines the recyclability of the products made by 3D Printing. As Sauerwein et al. (2019) pointed out, the recyclability of 3D Printing is extremely material-dependent. When products have very complex shapes, once they are broken, it's very difficult to repair them, and in these circumstances it's better to just replace them with new ones. When this happens, the recyclability of materials used to make the already broken products is the main priority. If the products are made from recyclable materials, they can be recycled and become the materials to produce new products, which is a good way to close the resources loop.

For now, the availability of recycled AM materials is limited, but 3D printing materials are developing in a sustainable direction, there are more and more studies being developed on sustainable alternatives for 3D printing materials, also considering the possibility offered by the Liquid Deposition Modeling (LDM) 3D printers.

In addition, advances in 3D printing feedstocks using natural derived materials have been made recently, we can directly use biopolymers like the very common PLA, or other biobased, biodegradable, and recyclable materials for 3D printing (Liu et al., 2019), as bioplastic made from algae or with orange peels.

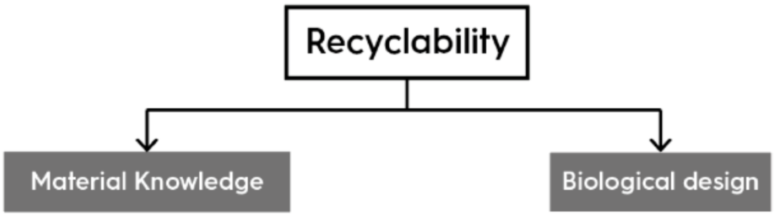

Figure 4: Recyclability influence on designer.

Distributed Manufacturing

Srai et al. (2016) define Distributed Manufacturing as the ability to personalize product manufacturing at multiple scales and locations, exemplified by enhanced user participation across product design, fabrication and supply, and typically enabled by digitalization and new production technologies. Shorter supply chains, reduced transportation, decreased overproduction through on-demand supply, and localized repair and recycling are the advantages of Distributed Manufacturing and why it is seen as a potentially sustainable alternative for centralized mass production (Ford & Despeisse, 2016). And the emerging characteristics of Distributed Manufacturing that distinguish it from centralized production are concluded as follows:

- Digitalization of product design, production control, and demand and supply integration that enable effective quality control at multiple and remote locations
- Localization of products, point of manufacture, and material use enabling quick response and just-in-time production
- Personalization of products tailored for individual users to support mass product customization and user-friendly enhanced product functionality
- New production technologies that enable product variety at multiple scales of production, and as they mature, promise resource efficiency and improved environmental sustainability
- Enhanced designer/producer/end-user participation, unlike the world of the artisan, enabling democratization across the manufacturing value chain

3D Printing supports Distributed Manufacturing since the digital file can be sent to production locally and Distributed Manufacturing can in turn solve the problems of low resource utilization and unsustainability caused by the uneven distribution of 3D Printing equipment (Howard, 2017). As the performance of consumer 3D printing improves, there is a convergence between consumer 3D printing networks and inter-organizational industrial 3D printing networks.

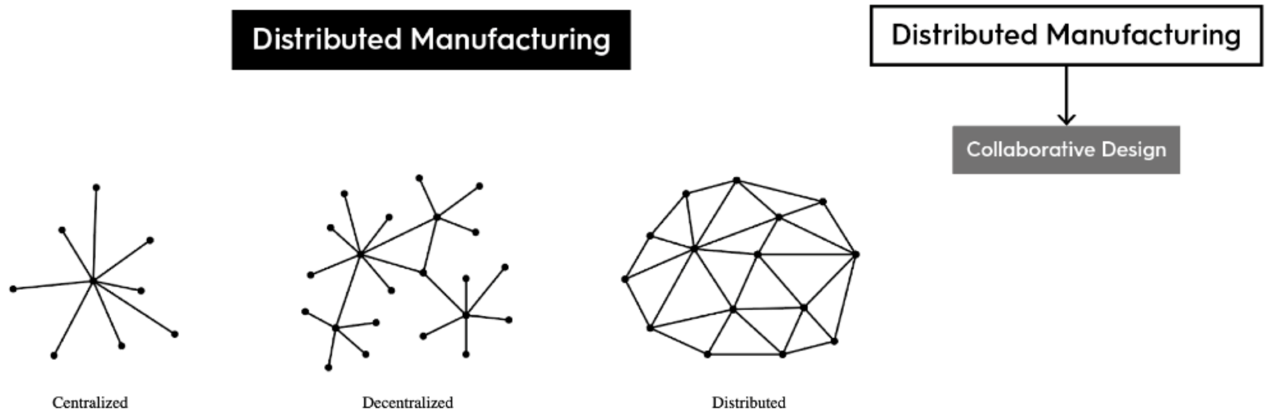

Figure 5: Distributed Manufacturing influence on designer.

Discussion

Thus, the five drivers presented can be viewed as strategies for efficient conscious and sustainable use of AM. However, they are not to be effective and functional for the activation of an AM-based circular design and manufacturing supply chain if viewed in isolation. Attachment, Recyclability, Reparability, Efficiency and Distributed Manufacturing can be functional and take on qualitative value in different design phases. In this regard, a roadmap is proposed as a graphical format in Figure 6 for better understanding and using the strategies within a design pathway that consciously integrates AM into sustainability and circularity.

Thanks to this graphical summary, it is appreciable how between the definition of the project objective and the release phase of the final result, there are the various steps of the design path that can accommodate influences brought by these strategies to go on to create effective and efficient design solutions for users, production, and environmental system.

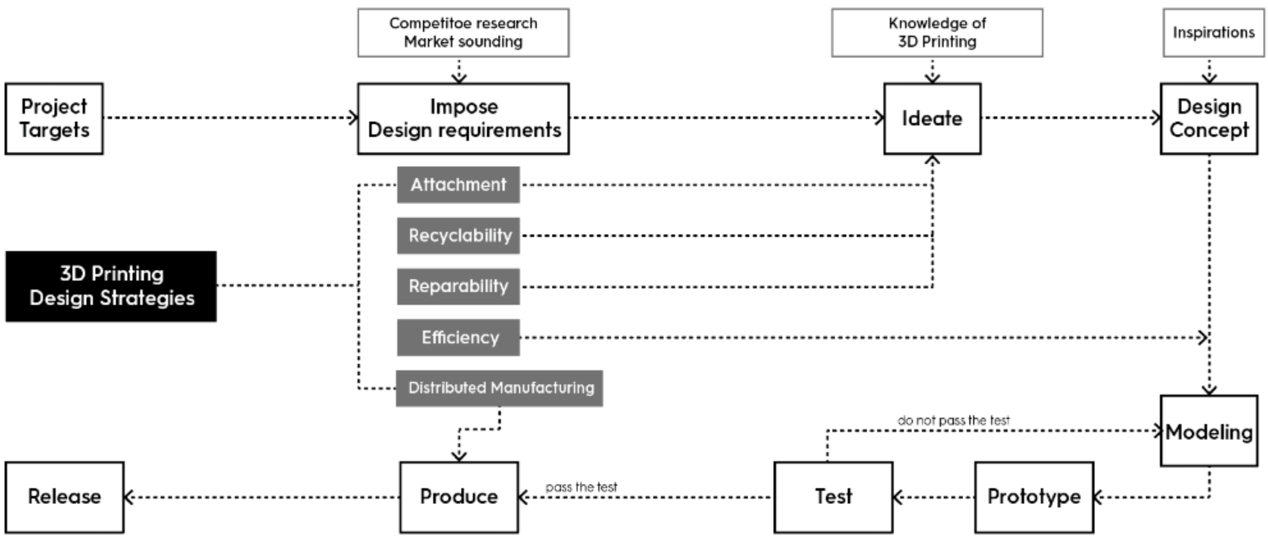

Figure 6: 3D Printing Design Strategies Roadmap

The need for specific prior knowledge

However, the identification of these strategies and their dissemination to a specialized audience cannot be considered a sufficient condition to wish that the use of AM will take place in a more conscious way and could facilitate the achievement of sustainable development goals. When one wants to convey change and expansion of opportunities, it is important to train the younger generation so that they can be active carriers of a change of pace. And in this specific case, it is important to go out and train the new generations of designers through a necessary updating of the content delivered in Design training courses.

Infact, to better make use AM, designers need to know better about 3D Printing technology, this is the prerequisite to applying 3D Printing to design projects. Technical specifications, working principles, use process of 3D printing, types of 3D Printer, strengths and drawbacks of different printing technology and so on, designers need to master the knowledge. And this is a requirement to encourage the foundation of implementing the five 3D Printing Design Strategies.

Training in 3D modeling software, understanding mechanical and physical processes, and materials knowledge are topics currently covered in the curricula of the Schools of Design. However, these topics are not functionally presented to explore the possibilities offered by AM, so students are not prepared to properly interpret additive technology. As introduced initially, they see it as an inexpensive alternative for creating study models or presenting design solutions designed for other production pipelines. Therefore, it is important to intervene in the structuring of the course of study of the Design educational realities to find the right space in which to convey structured information and skills, based on the PBL approach, in order to change misbehaviors and constitute a group of informed designer.

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