Attributes relevant for sustainable additive manufacturing – material driven approach

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Abstract. Additive manufacturing (AM) covers variety of applications in industrial manufacturing, healthcare industry, as well as 3D home printing desktop applications. It has significant contribution in the manufacturing technology development, while simultaneously creates an impact on the economy of scale. The production cost of AM is almost linear, regardless of the size of the production batch. Furthermore, an increasing parts complexity does not necessarily mean an increase of the production costs. It offers new degrees of freedom in the product design, enables reengineering and redesign, and facilitates resource optimization (energy and materials) and waste reduction. At the same time, it promotes reducing the number of assembly operations while contributing to more energy efficient and more cost-effective production. As one of the mostly spread AM technologies, which is quite limited in terms of material selection but has numerous advantages, e.g. during crisis that imply supply chain disruptions, the focus of this paper is on the 3D printing features. In particular, with the assistance of Multi Attribute Analysis, this study elaborates and identifies relevant attributes describing the 3D printing process and its features through the perspective of materials susceptible to 3D printing. The holistic approach presented in this paper introduces a new perspective for decision makers in the field of 3D printing, because in addition to the traditional material selection process, introducing attributes relating only to cost and manufacturability, it includes attributes describing the extended sustainability paradigm. The approach presented herein, categorizes attributes describing the 3D printing process in five main groups, i.e. economic, social and environmental (corresponding to the sustainability paradigm), amended by the technical and legal aspects.

1. Introduction

The contemporary manufacturing industry is facing dramatic changes especially with the recent fast developments in the digital technologies. One of the most significant moments of this change is the invention of advanced manufacturing technologies, such as Additive manufacturing (AM), an important driver in terms of small-scale production enabling improvements both in cost and resource efficiency. [1] Namely, the basic principle of AM technology is that a model, initially generated using a three-dimensional Computer Aided Design (3D CAD), can be produced directly without process planning, which usually requires complex and expensive tools and machines. AM technology significantly simplifies the process of producing complex 3D objects directly from a CAD model
(digital model), without the need of traditional tools specialized for separate operations (casting, forging, etc.). Following the 3D model features, the product is manufactured directly on the designated building platform, by adding layer over layer of a selected material. [2]

The variety of AM technologies, are classified by a corresponding variety of criteria. One of the classification approaches is according to the used baseline technology (lasers, printer technology, extrusion technology, etc.). [3, 4] Another approach based on layer manufacturing (LM) process and type of used material [5] is presented on figure 1. [2] Although 3D printing falls under a broader set of AM technologies, among the wider public and even professionals, not completely justified, AM is often referred to as 3D printing.

![Figure 1. Additive Manufacturing (AM) classification based on Layered Manufacturing (LM) processes and used materials][2]

Further development of AM, as well as, other advanced manufacturing technologies will significantly affect the supply and value chains. In terms of reconfiguration of the value chains, shorter and simpler supply chains, more localized production, innovative distribution models and new forms of collaboration, 3D printing significantly influences the structure of material supply chains. Thus, 3D printing affects not only the economy of scale, but also the economy of scope as it reduces the need to hold large inventory. [6, 7]

Since in the context of Industry 4.0, AM technology emerges as one of the key concepts of the next decade, the corresponding aspects of sustainability are very important. Apart from the economic aspects, to date, investigations by researchers into the sustainability implications of AM have either been done at a broad level [7, 8] or have been highly focused on the issue of material and energy consumption. [9, 10] AM technology originally used polymeric materials, waxes and paper laminates. The introduction of composites, metals, and ceramics, was a significant step forward. [2] Materials have been carefully selected to closely suit the operating parameters of different processes and to provide better quality and accuracy of the final parts. In addition, the enriched set of available materials, have resulted in the processes being tuned to produce goods that withstand higher temperatures, smaller feature sizes, and improved productivity. On the other side, constant enriching materials have resulted in the processes being tuned to produce goods that withstand higher temperatures, smaller feature sizes, and improved productivity. On the other side, constant enriching
of the set of available materials for 3D printing increases the complexity of the material selection process. AM offers several new degrees of freedom in the product design and production processes. The additive nature of this technology (adding layer over layer), means that products with complex inner structures could be produced (printed) at no additional cost. [11] This enables designing and manufacturing more complex structures (enriching the design spectrum, material saving and weight reduction, reducing assembly efforts in part production, etc.). [12] Simplified assemblies with less material diversity, improve the opportunities for recycling.

The CoViD-19 pandemic brings out the importance of localized, small scale (and on demand) production of variety of products (final or intermediate, such as protection shields or their parts, valves for respirators or their parts, etc.) which have a tremendous impact on the health system support. Moreover, the shift toward a decentralized manufacturing implies that the environmental impact of goods transport is reduced, while supporting and empowering local communities. In addition, AM allows conversion of waste and by-products into new products. [1]

This paper focuses on the specifics of the 3D printing, widely used, not only by professionals but by numerous of enthusiasts in the field of digital technologies. 3D printing, requires relatively simple equipment (home 3D printers), and it is predominantly based on the knowledge and experience of the skilled enthusiasts. Exploring the topic of 3D printing through the attributes of the materials used, a more comprehensive understanding of 3D printing sustainability is provided via multicriteria decision analysis (MCDA).

2. Methodology: Multi criteria decision analysis
Decision-making is the study of identifying and choosing alternatives to find the best solution based on different attributes/criteria, while considering decision-makers’ preferences. Materials selection process is a multifold problem, which optimally should result in finding the best option comprising material properties and design features with fulfillment of the products life cycle sustainability requirements. [13] The basic procedures for addressing conflicting and intrinsically not comparable aspect/requirements, are covered by Saaty [14], Goicoechea and Duckstein [15], etc., while their solution is offered via multi-criteria decision analysis (MCDA). This major class of methods is further divided into Multi-objective decision-making (MODM) and Multi-attribute decision-making (MADM). [16] MODM involves multiple conflicting objectives, while MADM deals with small number of alternatives and their assessment against a set of attributes, often hard to quantify. [17] These methods are favorable when decisions are to be delivered in challenging and complex environment and derive solid results. It should be emphasized that different methods and the correspondent results are not necessarily comparable. The first step in performing MCDA is problem definition, performed by setting the main goal, identifying attributes and sub-attributes, as well as considering relevant constrains and uncertainties. Criteria relevant for the decision are defined based on the decision-makers preferences (in this case the manufacturer/designer as in 3D printing these two roles are interwoven). Furthermore, the alternatives are defined, representing possible options for reaching the main goal. Once the model hierarchy is created, the next step is to determine the weights of the criteria against which the alternatives should be assessed and ranked. The criteria weights present their relevant importance versus each group of attributes and sub attributes. After ranking the alternatives, the set of the top - ranked, shall be accepted as an optimal solution addressing the main goal of the predefined problem.

The herein presented work focuses on defining the problem hierarchy and identifying the attributes, sub-attributes and alternatives. Thus, material driven identification of relevant attributes for sustainable 3D printing practically implies evaluating material alternatives versus the attributes describing the extended sustainability paradigm (technical, economic, social, environmental and legal attributes).
3. Selection of material for 3D printing via the extended sustainability paradigm

Sustainable manufacturing, in general, denotes manufacturing products by means of processes with minimal negative environmental impact, remained resource efficiency (energy, water, materials input), employees, communities and consumers safety, while contributing towards improved societal benefits. From the perspective of material usage, 3D printing (as well as AM), in general, is more efficient. Namely, based on layer-by-layer fabrication, material waste in 3D is significantly reduced. [18] In addition, the properties of the supporting material utilized to make increasingly possible complex geometries, allows recycling into raw material, after the 3D printing of the desired product is finished. Meanwhile, many CNC machined (and in general in subtractive/traditional production) parts are produced from block, which is always significantly bigger than the produced part, leading to up to 19:1 ratios of material waste versus the material embedded in the final part. [19, 20] Besides the fact that 3D printing is inherently less wasteful than the traditional subtractive methods, it has a potential to decouple social and economic value creation from the environmental impact of business activities. [2, 19]

Although the materials used for this technology are not always greener than those used in traditional manufacturing, its sustainability advantages are obvious, regardless of the used material. [10] The material analysis throughout the product Life Cycle Assessment (LCA), significantly affect the sustainability of the overall 3D printing process. Moreover, the fact that the majority of the used materials are based on thermoplastics (extrusion process) [21], originating either from fossil fuel (mostly) or bio-based feedstock (in rare cases), the material analysis versus the herein utilized extended sustainability paradigm gains in complexity. This complexity drives the increased development of a whole range of new materials suitable for 3D printing. Since the main characteristics of interest in terms of manufacturability are the melting temperatures, melting viscosity and coagulation time, the two dominant thermoplastics are acrylonitrile butadiene styrene (ABS) as a fossil-based plastic and polylactid acid (PLA) as a plastic. In relation to 3D printing, combined with (bio) additives to create special properties, a whole range of bio plastics is under development. [22]

Material selection suitable for sustainable 3D printing process, commences with identification of the relevant material attributes and sub-attributes, which correspond to the extended sustainability paradigm. The vision for sustainability encapsulated in the Brundtland Report [23], was groundbreaking, but recently numerous authors address the need to extend it on a broader context, having in consideration public policies and legislation, corporation decision-making, and other causes of sustainability threats. [24] Namely, 3D is closely interlinked with legal aspects of this process, focused on intellectual properties, patent law, standardization and consumer protection. [12] On the other side, according Ashby & Johnson [25] classical theory, materials attributes (based on designer perspective) are categorized as basic, technical, aesthetical and environmental. Thus, the material selection should be carefully performed considering not only the availability, costs, (material costs, machining costs, man hour costs, etc.), manufacturability, as well as taking into account the environmental and social impact. The decision maker (in this case, both in the role of designer and manufacturer) should be equally responsible and aware for the product quality, price and its environmental impact. The manufacturing constrains, customer requirements and design guidelines should be balanced in a way that minimizes overall (direct and indirect/external) costs and maximizes product quality and social benefits. [13] The technical aspects present a set of features affecting product quality in the terms of accuracy, surface finish, product lifetime, etc., but in the same time simultaneously encompass certain limitations of product size and shape. Thus, carefully performed material selection is very important precondition for optimal design and manufacturing process, and for obtaining accepted and durable final product with minimal environmental impact. Merging all aforementioned aspects results in the s.c. extended sustainability paradigm, which combines the classical definition of sustainability with the classical theory of Ashby & Johnson for classifying material attributes [25], while upgraded by adding legal aspects, as it is shown on figure 2. Thus, the hierarchy structure (model) of the analysed
problem, encompasses attributes and sub-attributes arranged in two hierarchy levels, having in mind the numerous and often conflicting criteria specified by the stakeholders. The first hierarchy level lists the five classes of material attributes (technical, economical, environmental, social and legal), in line with the above proposed extended sustainability paradigm. [12, 25, 26]

![Problem hierarchy in line with the extended sustainability paradigm consisting of five categories of material attributes](image)

3.1 Identification of attributes and sub-attributes

**Technical attributes and sub-attributes.** Among the identified five main group of attributes, this group gains in complexity because the material properties, machining features and design possibilities are strongly interwoven. E.g. manufacturability depends on the material type, but is also related to the geometry complexity as well as the equipment limitations, whereby all these factors vary significantly for different materials. Further, the design process is a synthesis of numerous factors based on the material properties and manufacturing possibilities, aimed towards obtaining a product suitable for the life-cycle objectives. Moreover, different possibilities exist contributing for an extended product life (based on the type of used materials), by using technical approaches such as repair, remanufacture and refurbishment. On the second level, the following technical sub-attributes are identified:

- **Material strength properties.** (e.g. Thermal expansion Coefficient (K-1), Young Modulus (MPa), Material Yield Strength (MPa), Hardening factor (-), Anisotropic Strength Coefficients (-). These parameters define material behavior during the manufacturing process, also influence the final product quality and durability)
- **Surface finish.** (as related with the materials microstructure, anisotropy, fatigue cracks appearance and growth, defects, etc. It also depends from the manufacturing accuracy. Product manufacturing that does not require post processing is a significant driver towards sustainable 3D printing.)
- **Geometry complexity.** (Geometry limitations are present during 3D printing, and should be considered combined with the material properties. This sub-attribute includes recommended values in terms of wall thickness to assure accuracy (mm), minimum and maximum feature size (mm), minimal holes size (mm), machining allowance (mm) as well as the aspect ratio – the maximum ratio between the print height and width.) [27]
- **Machining accuracy.** (3D scanning techniques are usually used for machining accuracy process comparison. One of the most used method to determine the deviation between the products from different materials is the Root Mean Square (RMS)(μm).
- **Machining minimum layer thickness.** (Machining or printing minimum layer thickness (mm) is related with the materials strength properties)

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2 Yellow lines denote some of the correlations between different groups of attributes
- **Build volume.** (Limits the building platform space, and affects the product shape, size and cooling properties, depending on the usage of different material)

**Economic attributes and sub-attributes.** These attributes are predominantly related with material purchase and labor costs, but they also affect material efficiency rates due to the build speed (required time for production). Latter sub-attribute is again strongly correlated with the material properties (temperature distribution along the build product, cooling time and prevention of defects), thus the optimal manufacturing parameters should be adjusted based on the specific material features. Furthermore, by using the material properties as advantage, cost reductions could be obtained if the product shape is modified to fully exploit the 3D efficiency potential.

**Social attributes and sub-attributes.** All technologies are developed and adopted within the complex network of existing infrastructure, technologies, behaviors, norms and attitudes of its constituent parts. Employment and the distribution of labor, health and safety, ethics, quality of life, community empowerment, creativity and self-expression are just some of the aspects [1] Material properties and sub-attributes related with the surface finish influence the material (product) acceptance and the mainstream in consumption patterns. On demand and customer tailored manufacturing is a serious advantage when used materials are easy affordable and available.

**Environmental attributes and sub-attributes.** The environmental impact of the selected material can significantly vary depending on origin of the materials and chemical composition. Concerns such as toxic vapors related to some materials. They affect the occupational health of the workers, but could also have an influence in terms of product acceptability, despite their formal alignment with the legal requirements. Landfill waste and recycling possibilities are correlated sub-attributes, since the materials have different recycling potential. In addition, the available recycling infrastructure and know-how for recycling processes of each material type are very important, having in consideration that some of the materials are compostable. While in most regulations mechanical recycling is the preferred end-of-life solution, energy recovery via incineration is preferred over land filling. [28]

**Legal attributes and sub-attributes.** The decentralized market for production enabled by 3D printing unfortunately facilitates a decentralized market for piracy. In traditional manufacturing, the copying of a design can be readily traced to a source since an infringer requires an infrastructure for manufacturing. Intellectual property and patent law issues relating to the traditional manufacturing are more-or-less common for all types of materials used. Moreover, in terms of used material features, the aspects like the toxicity, consumer protection and quality assurance are in particular challenging for the legal framework.

3.2 Identification of alternatives (materials)
A set of materials for 3D printing is listed (as alternatives) in order to be assessed versus the above noted group of attributes. The list of materials is presented on figure 3.
The proposed list of materials is based on the focus of this paper i.e. 3D printing for customized manufacturing in small batches, where the manufacturer as well is the designer. The identified materials are easy affordable and available compared to some other more advanced options. At the same time, the intention was to extend the list with as much as possible material types that are fitting the purpose. The sustainability of the 3D printing materials is a challenge since predominately they originate from petroleum products (ABS, PVA, Nylon, HDPE, T-Glass/PETT, etc.) PLA is a biodegradable eco friendly material whose application is mainly concentrated in the food industry. The second column in the figure 3, lists the filaments materials that combine the properties of two or more materials in order to exploit their advantages (composites). Typically, wood filaments contain 70% PLA and 30% wooden fibres, but it all depends on the filament manufacturer. Metal filaments, also have PLA as a base, and contain very fine metal powder such as copper, bronze, brass, and stainless steel. The percentage of metal powder infused in each filament can vary depending on the manufacturer. The presence of the metal powder makes the filament much heavier than standard plastics, but provides much better strength properties. Conductive filament is a new emerging material type that is great for small electronic projects or small electronic circuits. “Conductive” means that electricity can flow through it. This filament often has PLA as a base material, but other materials (ABS, for example) are also used. Carbon fiber filaments are also composite materials that could increase the strength of the printed product. By means of combining the features of thermoplastics and elastomers, flexible filaments are obtained. They are soft and flexible, recyclable, resistant to chemicals and resistant to low and high temperatures. [29] Seen through the extended sustainability point of view, all these materials have their advantages and disadvantages in certain application depending on their cost, manufacturability, strength properties, environmental and social impact as well as legal constrains. Thus, the selection of the most suitable material responsive to all these requirements becomes more and more difficult task for decision makers.

4. Results and discussions
There are number of available and affordable materials for 3D printing applications. Their usage for manufacturing specific product could be fostered or inhibited depending on a complex set of attributes and sub-attributes, relevant for the sustainable material selection to be used for 3D printing. As aforementioned, the technical attributes are the most complex, but it must be emphasized as they have a strong correlation and influence over all other classes of attributes. Moreover, there is interdependence among sub-attributes, not only within their paternal class, but as well between the other four comprising the extended sustainability paradigm. Elaboration of the most important and notable interdependences are described below:
Technical attributes. Manufacturability of certain material is in correlation with the equipment features and process parameters, but it also affects the manufacturing costs, energy consumption, waste generation, recyclability, etc. Holding a database of digital designs allows products to be manufactured on demand. Optimization of process parameters in order to control temperature distribution and total deformation of the produced good (especially of complex parts) is also significantly affected by the selected material properties. Design optimization itself enables products improvements resulting in mass reduction. The potential for mass reduction of the products depends on the materials behavior in terms of geometry complexity sub-attributes.

Economic attributes. Economic attributes are defined by material costs (directly) as well as by productivity and resource efficiency (indirectly). They affect not only the direct cost (i.e. material purchase), but they also promote cost reduction by means of mass reduction (via design optimization), manufacturing time (related to the material manufacturability and required operational parameters), post processing and finishing operation requirements, as well as the product end of life costs. Moreover, the availability and easy access to the required (selected) material is very important.

Social attributes. The social dimension of 3D printing is very important in terms of local communities’ empowerment. Namely, the potential for local availability of the selected material as well as the potential for its local production, could affect the decision for material selection, having in perspective the benefits for the community. In addition, the democratization of production, the combination of information and communication technology (ICT), widely available CAD software and 3D printers is changing consumption pattern. It creates an environment where the communities’ cultural specifics and habits have key importance in materials acceptance. However, the consumers’ awareness both in terms of material quality and environmental impact must be taken in consideration.

Environmental attributes. E.g. potential material toxicity needs to be analyzed carefully, since it could offset the benefit from materials savings during the manufacturing process. Moreover, the energy usage related with specific material has a significant impact on the processing itself. The material recycling potential as well as locally available recycling infrastructure are also significant aspect of the environmental attributes. Thus, the full environmental performance of the entire product life cycle must be evaluated from a system’s perspective.

Legal attributes. Legal aspects of the problem are very complex since it involves new technology that requires specific legal and regulatory environment. Protection of consumers and quality assurance are important when it comes to new materials applications. There are still many open questions in this area, reaching from issues of intellectual property to complicated procedures for approval and certification. To enable a successful 3D printing surroundings, these regulatory challenges need to be solved in order to set the right boundary conditions. Since a number of 3D printing materials are toxic and cause toxic emissions during processing, occupational health and safety issues requires a serious review.

The sustainability in the process of 3D printing material selection could be improved not only by means of attributes and sub-attributes identification and analysis, but also by means of research and development of new more sustainable materials. The wider penetration of biodegradable plastics (PLA) and other eco-friendly filaments, will contribute for a more effective shift towards sustainable 3D printing.
5. Conclusions
There are numerous criteria related with the 3D printing material selection in accordance with the extended sustainability paradigm. Some of the criteria are not directly measurable and cannot be quantified. This is an additional burden for the decision makers. Moreover, the greater diversity of available materials brings additional complexity in the decision making analysis. The herein proposed concept identifies relevant attributes and sub-attributes that describe materials. It must be emphasized that these attributes and sub-attributes are closely interlinked both in terms of different classes and into the same class. The most complex is the technical class of attributes since it covers material mechanical properties, machining limitations, design advantages and disadvantages as related with the selected materials. They not only affect time and costs of the manufacturing, but also influence the environmental impact, changes in consumers behaviour and consumption patterns, requiring various levels of legal support. From a material selection perspective, all the above noted attributes have different importance. Due to the complexity of the analyzed problem, and the identified correlations, future work should be focused on quantifying the correlation and addressing this complexity. This extends to a correspondent selection of materials that optimally suit the predefined decision-maker (in this case in the role of both designer and manufacturer) criteria.

Abbreviations and acronyms
AM     Additive Manufacturing
LM     Layer Manufacturing
CNC    Computer Numerical Control
ABS    Acrylonitrile Butadiene Styrene
PLA    Polylactid Acid
MCDM   Multi Criteria Decision Making
MCDA   Multi Criteria Decision Analysis
MADM   Multi-Attribute Decision Making
MODM   Multi-objective decision-making
PVA    Polyvinil Alcohol
HDPE   High Density Polyethilene
RMS    Root Mean Square
ICT    Information and Communication Technology

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