An ad hoc decision support method over additive vs. conventional manufacturing

Stamatios Polydoras[1,*], *Clio* Vossou[2], and *Dimitrios* Koulocheris[2]

[1]NTUA, School of ME, Mechanical Design & Automatic Control Department, 15780, NTUA Campus, Zografou-Athens, Greece
[2]NTUA, School of ME, Vehicles Laboratory, 15780, NTUA Campus, Zografou-Athens, Greece

Abstract. The mechanical design process considers numerous factors. Requirements related to performance and quality, limitations by legislation, standards, methods utilized or technological boundaries, urgency, cost, data preparation and preservation, design flexibility and organizational aspects. Successful design consists of proper decisions on form, geometry, materials, manufacturing methods, quality, reliability and more. Nowadays, a critical decision during design and realization of technological objects is whether they should be made conventionally or with Additive Manufacturing (AM)/3D Printing methods. Such a decision occurs under time-pressure or via a broader strategy for technological switch, is complex, multi-parametric and bears uncertainty and risk. A simple, effective and substantiated method to assist decisions for switching from conventional to AM could prove very useful. This paper refers to recent trends and activity in international AM-related standards, then presents and discusses preliminary work of the authors for an ad hoc decision method to be used upon specific "go/ no-go" decisions for AM. The method is largely based on the Pareto principle, to limit critical design factors contributing to this decision. All steps of the method towards a final decision are described. The method is demonstrated with a hypothetical, yet realistic example of a short run coolant vessel manufacture.

1 Introduction – Industry 4.0, Modern Design, Additive Manufacturing, Standards & Decisions

The technical world has recently seen a lot of change. Priorities have shifted, from maximum cost effectiveness and performance-maximized products, towards sustainability with optimized products. Design cycles nowadays tend to actually never meet a specific end point, as modern products, are “open” for change or improvement, throughout their full lifecycle, [1]. The same applies for priorities and strategic goals of production organizations, both large and small, where sustainability, longevity, effective operational structure, ecologic consciousness and social reputation, increasingly emerge above short- or mid-term financial results.

* Corresponding author: polsntua@mail.ntua.gr

Inevitably, this new technical environment affects and alters the nature and characteristics of modern products, in terms of design approach & process, production methods and industrialization. The role of electronics, computers, digitalization, CAD, CAE, PLM, the Internet, the “Cloud”, Internet of Things (IoT) and other disruptive technologies, is crucial in this transformation, as they all formulate today’s Industry 4.0, [2].

Equally important, Additive Manufacturing (AM), or simply 3D Printing is also correctly regarded as a key technology of this modern technical and industrial environment, already drastically acting as the critical link between the new “digital/virtual” universe of products and their “on demand” materialization. Most AM technologies have originally appeared in the late 1980’s – early 1990’s as Rapid Prototyping Techniques, [3]. Having almost immediately proven their value in product development, the past two decades they have gradually evolved into a vast future-capital for modern product design, development and manufacturing in the era of Industry 4.0, [4].

Design, both organizationally, as well as geometrically, is already severely affected by AM’s special characteristics, adopting even more the concepts of individuality, customization & specialization, just-in-time & on demand production, minimization of inventories for products, parts and tooling as well, localization in production and product finalization, composite and multi-material components and of course, form-geometry-mass optimization, assembling minimization and parts consolidation, [5].

A reasonable question design & manufacturing-involved decision makers and industrial practitioners will soon have to often answer, is whether, when and why they should opt for an AM/3D Printing technology available, in place of a well proven conventional manufacturing method or process (e.g. casting, machining, forming etc.).

Modern mechanical products amass many of the following trends and characteristics:

- Global simplicity, individual/local complexity
- Interchangeability, physical and functional flexibility, upgradability
- “System-level” cross-platform compatibility, “system-level” modularity
- Increased “component-level” functional integration vs. modularity
- High-degree performance tunability/adaptability
- Easier assembly-disassembly; Reduced relevant time and effort
- Reduced materials’ diversity, materials and components re-usability and recyclability
- Minimization of standardized machine elements and connecting elements
- Incorporation of “smart materials”, “Built-in” Intelligence (AI)
- Easy-fast servicing, Easy-fast-cost effective repair

Obviously, incorporating the above characteristics into any modern product without a digital background would be from difficult to impossible. AM is directly involved with these when it comes to actual product realization. But, with AM still rapidly growing on capabilities, but equally on “inflated expectations”, it is really difficult one to monitor current state of the art and at the same time objectively judge for, or against AM. On the other hand, conventional methods, when compatible with a current need or application, being fundamentally simpler, cheaper and usually already highly optimized, offer a high degree of security to industrial operators.

In such cases a simple, fast, effective decision support method could prove useful, especially under time-pressure. To develop, implement and support such an ad hoc decision method, members of the technical community need to acquire and retain objective knowledge of the actual capabilities and limitations of modern AM in every industrial branch and here is where standards step in.

In the field of AM, the American Society for Testing and Materials (ASTM) – Committee F42 and the International Standardization Organization (ISO) – Technical Committee 261 shortly after, have both recognized the need to develop and establish standards for the “frantic” AM technologies, covering aspects from terminology, technologies and systems, to proper practice, materials, design guides, tests – measurements – reports, or special requirements by specific industrial branches. They have already jointly published and are currently developing many new fundamental and targeted AM-related standards. Knowledge of these standards can lead to knowledge on the AM technologies themselves and their successful implementation.

The most important already published and effective standards that relate with and can be utilized as props to assist decisions on AM implementation, in the authors’ opinion are: ISO/ASTM 52900:2015, ISO 27547-1:2010, ISO/ASTM 52901:2017, ISO/ASTM 52902:2019, ISO/ASTM 52910:2018, ISO/ASTM 52921:2013 and ISO/ASTM 52921:2013, [6]. Moreover, many more AM standards are imminent and currently under development, most important of which for decision makers should be: ISO/ASTM 52903-1, ISO/ASTM CD TR 52912, ISO/ASTM DIS 52921, ISO/ASTM DIS 52924, ISO/ASTM CD TR 52918, ISO/ASTM AWI 52908 and ISO/ASTM AWI 52909, [7].

A product is first born when expressed as an idea or need. Needs are translated into design requirements and later transformed into design specifications; the tangible goal every design has to meet, [8]. Requirements can be categorized into larger groups (e.g. performance, safety, economic, managerial, environmental, social, special etc.) containing specific design factors and each factor could also be further analysed into its constituent parameters, to make the design process both analytic and organized. The actual design outcome will comprise from appropriate techno-economic compromises that will best satisfy the mixture of attainable design factors, expressed within the design intent by preference and importance of each one.

It is a fact that the number of design factors and their parameters is very large, [9], making all decisions in the process more difficult to implement and harder to justify. A useful solution to this inefficiency comes from the Pareto principle, often applied in many technical problems and stating that only a 20% of crucial parameters in any problem is responsible for more than 80% of the outcome, [10]. This principle, in conjunction with “Miller’s law”, [11], regarding the maximum number of variables the human brain can successfully simultaneously handle, drastically helps all decision problems and is adopted by the authors in the proposed decision support method.

2 The proposed 7-step ad hoc decision method

In the proposed method, for the sake of speed and effectiveness, the “analysis” of design factors that determine AM fabrication over conventional manufacturing stops at the level of factors. Any design and manufacturing environment can formulate its own set of requirements and factors, overall, or per product. Not all requirements or factors would be applicable in every case and they could be selectively adapted for certain product or component types and categories. Apart from strictly product-specific design requirements, it is important for industrial operators to also include some strategic requirements, related to innovation and the dilemma of technological switch towards AM within an organization. The method is intended for decision makers closely related to the specific product’s development and with a clear understanding on the capabilities of their own organization, as well as modern AM developments, where again current standards can serve as a prop.

Having properly combined and adapted well accepted and widely used design factors, parameters and criteria, [9, 12], with current industrial practices & state-of-art and the scope of the proposed method, for easier user-level implementation the authors present in Table 1 below some suggested indicative typical groups of requirements and their respective factors.

Table 1. Requirements and respective design factors applicable in AM decisions.

Requirement	**Typical Factors**
Performance	Strength, speed, hardness, flow, max/min temp, …
Functionality	Ease, ergonomy, readability, interface quality, …
Efficiency	Consumption, efficiency ratio, operation time, …
Durability	Fatigue, hardness, resistance to humidity, radiation, chemicals, …
Materials	Organic, technical, magnetic, conductive, precious, bio-compatible, …
Form-Aesthetics	Size, colour, texture, free forms potential, …
Manufacturability-Industrialization	Minimum part count, streamlined production, production rate, assembling time, assembly operations count, …
Reliability	Time to first failure, uses until failure, MTBF, …
Safety	Physical, electrical, toxicological, chemical, biological
Eco-friendliness	CO_2 impact, material recyclability, re-usability, raw materials efficiency, auxiliary equipment, …
Cost	Material cost, production cost, labour cost, tooling cost, running costs, ROI, …
Technological Availability	Domestic availability, local availability, in- house/outsource, …
Innovation	Modern technology, keep up with competitors, contribute to progress

A first step for the presented method is to select the most influential/applicable factors from Table 1, or any similar list of the design team. No "requirement" category is necessary. All non–applicable factors can be omitted.

In the second step the Pareto principle is applied on the selected factors, to narrow them down to a manageable number. This can be done e.g. by directly ranking their importance individually in a "1 (not important) to 5 (Very/extremely important)" qualitative scale. Depending on their initial number, important factors can be filtered by keeping only those scoring a "4" or "5", or just the latter; always trying to end up with a maximum of ten to fifteen "factors" for the assessment, to best satisfy "Millers's law".

A third - very important - step is to classify the remaining factors to those "in favor of" or "against" AM implementation, or else to those supporting – benefiting – justifying the use of AM and those that hinder – oppose – prevent it. If a factor is more or less equally served by both examined alternatives it can also be omitted as neutral. By the end of this step we should have two columns with the most dominant factors "for" and "against" AM.

Obviously, not all remaining important factors have the same impact or effect in the decision. For, or against AM, the preference, importance or utility of each factor on behalf of the decision maker must be registered in this fourth step as weights, in order to next reach a weighted aggregation. Pairwise comparison/ eigenvector method, [13], the "digital logic" approach, or even an arbitrary distribution of these weights must be implemented at this stage.

Some special handling is necessary for some critical factors that can act as "on-off" switches for the decision. We could name those factors "on-off" determinants or more aggressively "terminators". An example of such a factor for an assessed component would be under the "Materials" requirement group, the "Conductivity" factor. Given that an examined method, combined with a specific material would clearly lead to either a conductive, or a non-conductive part, such a factor – when required – will not be classified at all in the "for" or "against" columns for later scoring and weighted aggregation. In the method's fifth step, "terminators" are used more dominantly, as external multipliers of the weighted scores of each alternative, them always holding a "digital" value of "0" or "1" that allows them to totally terminate an option/alternative if not met by it.

During the method's sixth step, all already distributed important factors for AM or conventional manufacturing must now be ranked by the decision makers in a scale of only a few, positive-only, grades, e.g. "1: fair, 2: adequate, 3: good", corresponding to their satisfaction by their governing alternative, always with a specific method in mind and the available knowledge about their characteristics and performance (e.g. SLS of thermopolymers vs. Injection Moulding).

For the last seventh step, the product of corresponding weights with factors' grades is aggregated per column and multiplied with respective "terminators", ultimately leading either to the immediate elimination of an alternative (if zero-ed by a "terminator"), or to a final comparison between two positive total scores, one "for" AM and the other "against" it. The decision leans towards the greater number between the two.

An algebraic expression for the described method would include all the *n* important factors remaining after implementing Pareto filtering and "terminator" exclusion to be included in an **F** matrix, dimensioned 2xn, whose first column would contain values "1 to 3" for factors in favor of AM and "0" for factors against it. Respectively, the second column would include values "1 to 3" in all rows where column 1 had zeros and a zero in rows where in column 1 there was a value. **F** would be multiplied with a 1xn matrix **W** of weights, whose all elements sum up to 1. The result, driving the decision, would arise in a 1x2 matrix **R**, as expressed below,

$$\mathbf{R}=\mathbf{K}\times\mathbf{W}\times\mathbf{F}, \tag{1}$$

, where

$$\mathbf{K}= [\ \Pi k_i\ (i=1\ldots m) \quad 1] \tag{2}$$

, k_i = 0 or 1, m: the number of "terminators" applicable

If the 1st element of **R** is a number greater than the 2nd, AM should be opted for.

3 Discussion, conclusions & further work

Suppose an auto-industry subcontractor needs to manufacture a container for a relatively corrosive coolant, in a series of 50 to 500 pieces. The quantity of the coolant would be 0.5l and it could reach a temperature of app. 80°C. They need to examine if they should produce the part utilizing blow moulding of a proper plastic or use SLS in Nylon for the desired part. The Pareto-important factors for this specific case that falls in the category of a short-run production, as selected and filtered according to authors' prior technical experience, are listed in Table 2, and classified as "for" and "against" AM having followed the steps of the proposed method. The same applies for the importance weights (aggregating 1), that could of course also be derived by any valid relevant preference capturing technique, [13].

Table 2. Example important factors, distribution, "terminators" and weights.

Factors	pro AM	contra AM	"Terminator"	Weights	Grade
Flow	*			0.02	3
Water tightness			*	-	-
Transparency			*	-	-
Chemical resistance		*		0.1	3
Thermal resistance		*		0.1	2
Free Form potential	*			0.13	3
Impossible drafts	*			0.03	3
Minimum part	*			0.1	3

count					
Time to 1st Failure		*		0.02	1
Materials Efficiency	*			0.1	2
Auxiliary equipment	*			0.07	3
Tooling cost	*			0.2	3
Local availability		*		0.03	2
Competitors	*			0.05	2
Progress	*			0.05	3

Following the proposed method with the data of Table 2, we end up with a result vector of R = [2.1 0.58], namely AM is advisable for this specific case, provided that both "terminators" are satisfied (value=1) for the proposed AM solution. Nevertheless, examining more cautiously the characteristics of Nylon SLS, we can easily find out that there is no transparent Nylon powder in use for SLS. So, the correct result should eliminate this solution with the respective "terminator". Therefore, we should either relax the transparency requirement to an opaque vessel, or examine a different AM method, such as a UV resin-based method in order to proceed with the AM method.

The proposed decision support method is generic, fast, concise, simple, substantiated and relatively easy to implement, without the need of any special software package. It requires proper knowledge of the examined alternatives, thus probably calling for some collaboration of design teams and manufacturing experts during its implementation.

Several variations and improvements to the method could be applicable and are currently examined by the authors, as e.g. the simultaneous contribution of a single factor to both alternatives, the extension of the concept of "terminators" also to the conventional processes, the method's verification via sensitivity analysis etc.

References

1. M.E. Porter, J.E. Heppelmann, Harv. Bus. Rev., **93** (10) 96 (2015)
2. R. Y. Zhong, X. Xu, E. Klotz, & S. T. Newman, Engineering, **3**(5), 616 (2017)
3. C. K. Chua, K. F. Leong, & C. S. Lim, *Rapid prototyping: principles and applications,* World Scientific Publishing Company, (2010)
4. U. M. Dilberoglu, B. Gharehpapagh, U. Yaman & M. Dolen, Proc. Manuf., **11**, 545 (2017)
5. M. Kumke, H. Watschke & T. Vietor, V. & Ph. Prot., **11**:1, 3 (2016)
6. ISO, Standards by ISO/TC 261, Additive manufacturing, Published standards, Retrieved from www.iso.org on 28-04-2020
7. ISO, Standards by ISO/TC 261, Additive manufacturing, Standards und. Devel., Retrieved from www.iso.org on 28-04-2020
8. S. Eppinger, & K. Ulrich, *Product design and development*, McGraw-Hill Higher Education, (2015)
9. Y. S., Chen, P. P. Chong, & M. Y. Tong, Math. & Comp. Mod., **19**(9), 61 (1994).
10. S. Dowlatshahi, The Int. J. of Adv. Man. Tech., **9**(5), 324(1994)
11. G. A. Miller, Psyc. Rev., **63**(2), 81 (1956).
12. M.Sfantsikopoulos, *Mechanical Engineering Design Vol.I,* Athens, NTUA Publications (2005)
13. P. Sen & J. B. Yang, *Multiple criteria decision support in engineering design (Vol. 4).* London: Springer (1998)