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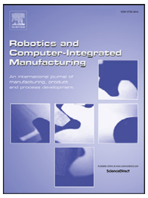

Integrated product-process design: Material and manufacturing process selection for additive manufacturing using multi-criteria decision making

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ABSTRACT

Market dynamics of today are constantly evolving in the presence of emerging technologies such as Additive Manufacturing (AM). Drivers such as mass customization strategies, high part-complexity needs, shorter product development cycles, a large pool of materials to choose from, abundant manufacturing processes, diverse streams of applications (e.g. aerospace, motor vehicles, and health care) and high cost incurred due to manufacturability of the part have made it essential to choose the right compromise of materials, manufacturing processes and associated machines in early stages of design considering the Design for Additive Manufacturing guidelines. There exists a complex relationship between AM products and their process data. However, the literature to-date shows very less studies targeting this integration. As several criteria, material attributes and process functionality requirements are involved for decision making in the industries, this paper introduces a generic decision methodology, based on multi-criteria decision-making tools, that will not only provide a set of compromised AM materials, processes and machines but will also act as a guideline for designers to achieve a strong foothold in the AM industry by providing practical solutions containing design oriented and feasible material-machine combinations from a current database of 38 renowned AM vendors in the world. An industrial case study, related to aerospace, has also been tested in detail via the proposed methodology.

List of Abbreviations

3DP	3D Printing
ABS	Acrylonitrile-Butadiene-Styrene
AHP	Analytical Hierarchy Process
AM	Additive Manufacturing
APF	Arburg Plastic Freeforming
CAD	Computer-Aided Design
CE	Concurrent Engineering
CJP	Color Jet Printing
CNC	Computer Numeric Control
DfAM	Design for Additive Manufacturing
DFM	Design for Manufacturability
DLP	Digital Light Processing
DMP	Direct Metal Printing
EBAM	Electron Beam AM
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
IPPD	Integrated Product-Process Design
LENS	Laser Engineered Net Shaping
LMD	Laser Metal Deposition
LOM	Laminated Object Manufacturing
MCDM	Multi-Criteria Decision Making
MJM	Multi-jet Modeling
MPS	Material Process Selection
PC	Poly-Carbonate
PP	Poly-Propylene
SAS	Slide and Separate
SAW	Simple Additive Weighting
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

1. Introduction

Since the inception of Additive Manufacturing (AM) as Stereolithography (SLA) by 3D systems in 1987, AM has taken up a significant and

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impressive compound annual growth rate of 26.2% to attain a market worth of $5.165 billion in 2015 [1]. Reduced product development cycles, increased and revamped regulations on sustainability, increasing demand for personalized and customized products, enhanced part-complexity, reduced lead times and manufacturing cost, increased throughput levels, and the introduction of new business models, are some of the many market factors that have assisted the associated growth of AM to produce complex parts in small to medium sized batches [2,3]. Moreover, the quantity and variety of End-of-Life (EoL) products in recent years has demanded the AM production systems to be designed in a sustainable manner such that the economic and environmental impacts are reduced [4]. This also includes the need for post-processing for issues such as removal of powder, support structures, platforms and polishing, as the surface quality may limit the application of the part produced [5]. As a result, the existing vast field of processing technologies and competitors in the hardware space of AM have all been found chasing diverse goals to simultaneously design a product, select a compromised material and pick a suitable fabrication process. This concept further comes under the domain of Concurrent Engineering (CE) and Integrated Design (ID) which help in not only reducing product development time, design rework, and cost, but also in improving communications between different functions of the total product development cycle by making upstream decisions to cater for downstream and external requirements [6,7].

As CE/ID is an attempt towards the integration of product and process plan parameters, the selection of the ‘best compromise’ of materials and manufacturing processes from a pool of over 80,000 materials, to not only satisfy the customer needs and functional specifications but also account for the process specific constraints, is a daunting task within itself. Some researchers have also referred to conceptual process planning to estimate the manufacturability and cost of conceptual design in early parts of the design stages [8]. But since AM has the capability to operate potentially constraints free, it has invited new heights of design freedom by offering enhanced complexities in terms of shape, multi-scale structures, materials and functionality [9]. It can also build parts in a single operation without wasting much raw material [10]. The subsequent realization has convinced the designers to use the Design for Additive Manufacturing (DfAM) guidelines to develop an integrated approach in the design stage wherein integrated product development teams manage to lessen and even vanish many manufacturing factors and constraints associated with traditional machining, such as, developing a modular design, using standard components, avoiding separate fasteners, and minimizing assembly directions, to attain parts of any geometric complexity without traditional machining aids such as tooling [11–13]. Moreover, as AM has the capacity to fundamentally change the way in which products are made and distributed, it has become a ‘disruptive’ technology marking its foot hold in nearly all areas of applications. Cotteleer et al. [14] and Sharon [15] divided these into seven areas: aerospace; health care; motor vehicles; consumer products/electronics and academic institutions; industrial applications; architecture; and government/military. Various ‘generic’ functionality indices and weights concerning multiple design goals, such as energy consumption, material strength, cost, environmental impact, and recyclability, are associated with each of the application areas and need to be taken care of appropriately. Furthermore, the suggestion of the compromised materials and manufacturing processes, referred to as the Material Process Selection (MPS) problem from now on, becomes an interdisciplinary effort keeping in view AM’s capacity to be both highly inclined towards CE / ID and governing multiple areas of application. This also proposes that several conflicting criteria will be associated with the MPS problem, which in turn must satisfy product’s life cycle requirements. Hence, such problems can be best handled using Multi-Criteria Decision Making (MCDM) methods [16].

Although many AM design guidelines have been published to cater for the process and machine specific constraints for a material, such guidelines could only provide a starting point and do not provide information about the different kinds of AM machines and their production capabilities [17]. Consequently, the objective of this paper is to provide a new generic decision methodology that can not only consider the interaction between product and process data, but is also be applicable on all areas of application using the MCDM methods; Ashby’s material selection charts and Analytical Hierarchy Process (AHP). The former method is utilized for screening of materials while the latter method is utilized for ranking of the combination of materials and manufacturing processes for AM. Combined, the method is called Integrated Product-Process Design (IPPD). Moreover, an AM machine database of 134 renowned machines from 38 international vendors along with AM-specific materials’ database is utilized to provide the most feasible material-machine combinations for a given design of product model considering product requirements, attributes and other function-related constraints and objectives. An industrial case study related to the aerospace industry is similarly presented to test the workability of the proposed methodology in detail as well.

The remainder of the paper is divided as follows: Section 2 presents the literature review of the IPPD concept in conjunction with DfAM and its subsequent relation with MCDM techniques related to MPS problem; Section 3 displays the proposed methodology; Section 4 displays the results for an industrial case study; Section 5 provides comparative analysis with another MCDM tool (Simple Additive Weighting), and finally, Section 6 discusses the conclusions drawn for a collaborative product development (considering product and process development).

2. Literature review

AM is defined by ASTM as the “process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing technologies like traditional machining” [18]. STL (STereoLithography or Standard Tessellation Language) is the standard file format used on various AM machines but there are other file formats such as SLI, SLC, HPGL, CLI, VRML, 3MF and IGES. Moreover, Monzon et al. [19] split AM in to 7 areas; vat photopolymerization (process that cures a liquid photopolymer contained in a vat by providing energy at specific locations of a cross-section), material jetting (process that uses ink-jet for printing), binder jetting (process which prints a binder in to a powder bed to form a part cross-section), material extrusion (process that makes a part by extruding material through a nozzle), powder bed fusion (process that uses an energy source like a scanning laser to selectively process a container filled with powder), sheet lamination (process that deposits material in form of layers), and directed energy deposition (process that uses a single deposition device to simultaneously deposit material and provide energy to process the material). The associated AM processes for each of the 7 classes are numerous; but, Huang et al. [20] provided a comprehensive overview of all the concerned classes along with their popular associated AM processes, materials used in those machines and their famous manufacturers as depicted in Table 1.

AM has the potential to simultaneously build an object’s material and geometry but considering unlimited potential does not guarantee having unlimited capability. The designers working in the AM industry have to not only concentrate on the types of constraints involved in procedures such as Computer Aided Design (CAD) and the digitization of its ideas [20], discretization (digital and physical) of the parts to be produced, assessing capabilities of AM machines, and processing of materials to gauge the impact on properties, but also cater for new challenges and requirements associated with metrology and quality control, maintenance, repair and recycling, lack of generic interdependency between materials and processes, limitation in material selection, longer design cycle than manufacturing cycle, surface finishing issues and post-processing requirements [21,22]. Since, the stakeholders in AM industry related to part manufacture are not altering the design completely in the ‘design phase’ thereby resulting in an increase in the costs incurred both due to manufacturability and production time, it is highly important to