Journal of Manufacturing Systems 37 (2015) 328–339

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory

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ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form 25 July 2014
Accepted 27 July 2014
Available online 28 August 2014

Keywords:
Additive manufacturing
3D printing
Multicriteria analysis
Data envelopment analysis

ABSTRACT

Additive manufacturing (AM) is an advanced technology where products are manufactured by building up thin layers of materials from digitized three-dimensional (3D) designs virtually constructed using advanced computer-aided design software. This freeform fabrication enhances dramatically the potential of design, pushing the boundaries of manufacturability. The aim of this paper was to provide a decision-making framework for the selection of an effective portfolio of production strategies, including alternative AM and traditional manufacturing technologies. To that end, a methodological framework is proposed which combines multi-criteria decision aid (MCDA) and data envelopment analysis (DEA) for the determination of the optimal production strategy within the concept of "focused" factory. In this light, modern AM technologies are assessed for a number of selected criteria (e.g. production cost, lead time, quality) together with existing production strategies that involve conventional production methods, such as injection molding, CNC machining, etc. The adopted framework is applied on a real-world case regarding the production of security keyboard polymer housings. According to the findings, modern AM technologies provide efficient manufacturing solutions for small production volumes, thus enhancing supply chain responsiveness through make-to-order strategy and customization possibilities. Furthermore, AM seems capable to contribute also to traditional mass production systems, by improving significantly the productivity of injection molds. The proposed framework could not only assist decision-makers in the selection of the optimal production strategy, but it could also provide crucial benchmarks for different production alternatives.

1. Introduction

Additive manufacturing (AM), often referred as three dimensional printing, was developed in the late 1980s with sales beginning to increase at a faster rate in early 1990s [1]. Despite the fact that it took almost two decades of research before AM became competitive to other traditional manufacturing technologies (e.g. [2,3]), AM is expected to considerably transform supply chains in the near future [4]. In comparison to traditional technologies, AM produces objects layer-by-layer, adding rather than subtracting material. Rapid Manufacturing (RM) has evolved through rapid prototyping (RP) due to technological advancements defined by Rudgley [5] as "the manufacture of end-use products using additive manufacturing techniques (solid imaging)". Given the scientific and technological advancements in the field of AM during the past decade, this work distinguishes between RM and RP due to the use of advanced printing techniques enabled by a range of sophisticated materials which facilitate manufacturing products with long term consistency for the entire product life cycle [6]. Rapid tooling (RT) is considered a sub-category of RM, which aims to create tools that serve traditional manufacturing procedures [7]. RT describes a process that is the result of combining RP techniques with conventional tooling practices to produce a mold quickly or parts of a functional model from computer aided design (CAD) data in less time and at a lower cost relative to traditional machining methods. RT typically, either uses a RP model as a pattern or uses the RP process directly to fabricate a tool for a limited volume of prototypes. The main advantage is that the tooling time is much shorter (less than one-fifth) than for a conventional tool. Moreover, tooling cost is also decreased. The main drawback however is that the tool life is shorter and the tolerances are wider. RT has been mostly used to create injection molds but recent developments now enable RT

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http://dx.doi.org/10.1016/j.jmsy.2014.07.014
0278-6125/

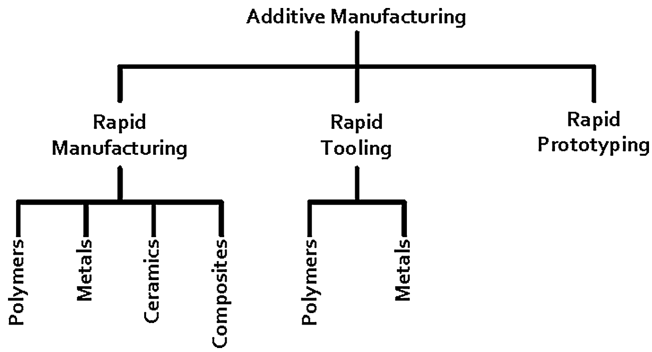

Fig. 1. Categories of additive manufacturing.

technology to be used for casting, forging and other tooling processes [6]. Kruth and Schueren [8] further partitioned RT into direct tooling in which molds are layer-manufactured for use, and indirect tooling where a master model is created and then used to produce a casted mold. A brief review of AM technologies and a snapshot of their current status is presented in the work of Campbell et al. [9].

Given the late great technological developments which introduced a wide range of different equipment and materials, AM processes can be categorized in many ways. As depicted in Fig. 1, AM processes use four large material categories, namely polymers, metals, ceramics and composite materials [6]. RM uses all four material categories, while RT uses only polymers and metals for tooling applications. Another categorization of AM processes can be based on grouping the processes according to material state and form as shown in Table 1 [10]. Three basic types of bulk material used are identified; liquid, powder and solid layers. Liquid material is used at processes like stereolithography (SL), fused deposition modeling (FDM) and ink jet printing (IJP), whereas powder is used for three dimensional printing (3DP), selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM) and direct metal deposition (DMD). Laminated object manufacturing (LOM) can use solid layers of any material category to create an object. In terms of materials used, polymers, such as polyamide, are still the most common. Polyamide reaches mechanical properties equal to components manufactured by molding, while also showing even improved properties in the case that it is glass bead reinforced [11]. Indicatively, in the production of metallic parts, DTM Corporation (Austin, USA) has developed a tooling process which applies polymer coated steel powder in which the polymer melts and acts as a binder during sintering and afterwards burned off in order for the porous area to be infiltrated with density improving bronze or copper [12].

Although, most industries still use RP to fabricate functional and conceptual prototypes, modern AM machinery is capable to transcend that. The late advances in the tooling industry offer new solutions (e.g. [2,13–23]). In the literature, studies based on cost-benefit analysis have documented that AM can be also economically viable for low volume production. In particular, Hopkinson and Dickens [24] compared different RM techniques against traditional injection molding in order to create a break even analysis, thus proving that AM seems appropriate for low volume production considering that production cost is constant, whereas the cost of an injection mold is amortized across the production volume. Furthermore, Ruffo et al. [25] developed an expanded estimation model using the full costing system. The authors argued that the RM process curve has a deflection for low production volumes in the cost–volume diagram, due to necessary processes which demand considerable time. In a later study, Ruffo and Hague [26] confirmed that manufacturing different parts in one build leads to cost reduction of each component. Walter et al. [27] documented that not only volume has to be considered in RM but also the scale of parts. The authors stated that the primary cost driver of a component is its size and not the production time required as occurs in conventional mass production systems.

This paper aims to provide a decision-making methodological framework for selecting AM techniques that may substitute traditional manufacturing technologies. The analysis is based on empirical research, conducted in order to provide evidence for the adoption of emerging new technologies [28]. More specifically, the proposed framework targets toward assisting manufacturers that have organized their production lines within the concept of a "focused" factory [29] to select the optimal production technique among available alternatives. In this light, modern AM techniques are assessed for a number of selected criteria (e.g. production cost, lead time, quality) together with existing production strategies that involve conventional production methods. The aim is to support manufacturers toward identifying the appropriate production strategy or portfolio of strategies for various families of Stock Keeping Units (SKUs). Focus is given on products and/or components which show a sporadic demand with a high coefficient of variation. For such SKUs, production planning constitutes a hard problem for manufacturers. The latter have a number of alternative choices; either (a) invest in the development of a "focused", tailor-made production line or job-shop that will be mostly unexploited due to the sporadic demand of the SKUs, (b) use existing production lines used also for the production of other products, or (c) select off-shore production with all its positive and negative characteristics [30]. In this light, flexibility of manufacturing systems is considered a critical parameter toward business success [31–33].

Table 1
AM processes categorized by supply material form and state.

Material form/state	Process	Materials
Liquid	SL	Polymers
	FDM	Polymers
	IJP	Polymers
Powder	3DP	Polymers, metals and ceramics
	SLS	Polymers, metals and ceramics
	SLM	Polymers, metals and ceramics
	EBM	Metals
	DMD	Metals
Solid	LOM	Polymers, metals, ceramics and composites

2. Impact of additive manufacturing on supply chain design

RM evolved as a modern AM process through RP. Although, both terms are still perceived as the same technology, RM seems capable to become a disruptive force, bringing drastic change to modern supply chains. While AM affects basically the "time-to-market", RM could affect the whole spectrum of modern supply chains and logistic networks. It would further require strategic business changes, such as increased collaboration and relationship with equipment vendors and material suppliers, since those are expected to become critical links of the supply chain [34].

Fisher [35] devised a seminal framework for supply chain strategy, based on the "functional" and "innovative" products' categorization. The design of supply chains for functional products with relatively predictable demand should be based upon an efficient strategy, whereas for innovative products it should mostly rely on responsiveness for those cases where product life cycles are short and variety is high [35]. The evident trend toward faster order fulfillment, shorter SKU lead times through complex supply chains and the increasing need of customization led to mass customization strategy [36]. Mass customization and high degree of flexibility seem to be the next steps of responsiveness, focusing