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Industrial Additive Manufacturing: A manufacturing systems perspective

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ABSTRACT

As Additive Manufacturing becomes increasingly prevalent in commercial manufacturing environments, the need to effectively consider optimal strategies for management is increased. At present most research has focused on individual machines, yet there is a wealth of evidence to suggest competitive manufacturing is best managed from a systems perspective. Through 14 case studies developed with four long-established Additive Manufacturing companies this paper explores the conduct of Industrial AM in contemporary manufacturing environments. A multitude of activities, mechanisms, and controls are identified through this detailed investigation of Additive Manufacturing operations. Based on these empirical results a general four component Industrial Additive Manufacturing System is developed, together with the identification of potential strategic opportunities to enhance future manufacturing.
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1. Introduction

The contribution and importance of Additive Manufacturing (AM) to commercial manufacturing practice has changed enormously over the last thirty years. Initially developed to produce prototypes for new products (termed 'Rapid Prototyping'/RP), as the technologies have improved their application has extended through to tooling ('Rapid Tooling'/RT), and more recently, to the direct production of end-use parts or whole products ('Rapid Manufacturing'/RM). Whilst a range of different successful applications has already been evidenced [1–7], numerous authors have identified that the technologies may yet invoke a new Industrial Revolution [8,9], and by 2025 it is estimated that AM could generate a global economic impact of $200bn–$600bn annually [10].

One aspect of AM that has not changed in its evolution is the overriding research focus on individual production technologies. Much detailed emphasis has considered opportunities afforded by AM machines, but this is often at the expense of the other critical components of the manufacturing system. Whilst there is no doubt that AM machines do indeed offer many unique capabilities, in terms of real-world manufacturing it is an oversimplification to assume that they do this alone. In practice a range of different resources support and compliment Additive Manufacturing, yet their contribution is seldom acknowledged in research. The proposition that one may 'just press print' to manufacture does not reflect current experience, and such overhyping of technological capabilities has the potential to disenfranchise potential adopters of AM [11].

Hence, whilst the technologies of AM are heralded as able to revolutionize future manufacturing [12], in practice current research approaches are often based on very traditional 'machine age thinking'. Such an approach is achieved through reductionism and mechanism [13], through which problems are broken down into their component parts for analysis and solution. This has led many researchers to focus purely on the capabilities of machines, and such approaches discount the important contribution of other resources in the achievement of 'manufacturing'. There are many studies that instead espouse the virtues of a systems approach in manufacturing [14–17], and in this paper we argue that a systems theory perspective is needed to better understand how AM may be used in real-world production.

This paper focuses on 'industrial' AM systems, and these are defined as having adequate maturity to be employed in the production of prototypes, tools, parts, or whole products in real-world manufacturing environments. This definition therefore excludes AM technologies that may be considered 'hobbyist', which are typically relatively inexpensive consumer-grade, and do not achieve quality or speed performance characteristics that make them suitable for commercial implementations. Industrial AM technologies may therefore be considered as being in competition with 'conventional' approaches to manufacturing,

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and an overview of the main Industrial AM technologies is shown in Table 1.

This paper commences with a review of the manufacturing systems concept, and identifies the limited attention this has been given for AM. Using data collected from four long-established firms that employ AM on a commercial basis, this study subsequently identifies the nature of Industrial AM Systems (IAMS) in practice. In doing so, this paper extends existing systems theory in the context of AM to identify the activities, mechanisms, and controls that enable real-world manufacturing to be achieved. This systems perspective provides an agenda for change for operations that employ Additive Manufacturing, highlighting strategic opportunities for enhancement throughout the system to improve operations competitiveness.

2. Literature review

2.1. Manufacturing systems

The origins of systems theory can be traced to parallel developments in a variety of scientific fields in the early 20th Century [19], but it was first popularized by the biologist von Bertalanffy [20], who promoted the expansionist agenda of 'wholes' and 'wholeness' in which interrelated elements which come together to form systems. Such an approach rejects a 'piecemeal' optimization of individual resources and instead allows complex problems to be addressed by examining a multitude of entities [21]. These entities are interrelated, systems subsume their individual parts [13], and the system as a whole displays properties that none of its parts or subsets has [19].

The application of systems theory in a manufacturing context has enjoyed considerable resonance, and has been identified as offering the potential to produce better solutions to manufacturing problems than any other approach [22]. The central objective of a manufacturing system is to transform raw materials into products, thereby gaining a higher value in the process [15,16,23]. To achieve this objective, manufacturing systems bring together a multitude of different resources [24], and these are organized and controlled to achieve optimal performance [16]. A manufacturing system therefore integrates activities, enabling mechanisms, and appropriate controls in the transformation of raw materials into finished products for the satisfaction of customer demand. Manufacturing strategy often focuses on the achievement of competitive priorities in terms of cost, dependability, flexibility, quality, and speed [25]. To achieve these capabilities, managers need to understand how all of their production resources can be leveraged in order to be most effective, and as manufacturing organizations have grown and increased in sophistication, the need to manage individual resources within a wider systems context has increased [24].

Manufacturing systems exist within the organization system [26,27], and whilst there is no single definition of a manufacturing system, it is acknowledged that a multitude of different system designs can be used to satisfy the requirements of the organization [28]. One particularly commonplace approach is the use of hierarchical breakdowns of the manufacturing system [29], which in practice involves consideration of the system at the factory level, subdivided into work centres/cells, and then into individual manufacturing resources [23]. Manufacturing systems therefore comprise a multitude of different resource elements such as machines, labour, and computer/information processing equipment [15,30], and these are employed to undertake a variety of activities to satisfy the objectives of the system. They exist as part of an overall company system, through which information and control passes between individual functional subsystems [26]. As a system comprised of subsystems of multiple elements, manufacturing systems should achieve an 'integrated whole' [15], for which the advantage over individual manufacturing resources is that a system's capabilities are greater than the sum of

Table 1
Summary of principal Industrial AM process types, technologies, manufacturers, and materials.

Process Type	Process Description (from ISO 17296-1) [18]	Focal AM Technologies	Principal Manufacturers	Principal Materials
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials	3D Printing (3DP)	Z-CORP 3D Systems	Various powers including plasters, sands, and composite materials.
			ExONE	Various powders including stainless steel, cobalt, aluminium, copper, and sands, together with a range of metal alloys that can be bound with appropriate liquid binders.
Direct Energy Deposition	Focused thermal energy is used to fuse materials by melting as they are being deposited	Laser Cladding Laser Metal Fusion Laser Metal Deposition	Trumpf	Various metal powders including stainless steel, cobalt, aluminium, and copper
			Optomec	Titanium, nickel, tool steels, stainless steel, cobalt, aluminium, copper, and various composites
Material Extrusion	Material is selectively dispensed through a nozzle or orifice	Fused Deposition Modelling	Stratasys	Various thermoplastics including acrylonitrile butadiene styrene (ABS), acrylic-styrene-acrylonitrile (ASA), polyamide, polycarbonate, polypropylene
Material Jetting	Droplets of build material are selectively deposited	Multijet Modelling	Stratasys 3D Systems	Ceramics, liquid photopolymers, melted waxes
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	Selective Laser Sintering (plastics)	EOS 3D Systems	Polyamide, polyaryletherketone, polystyrene, and various composites
		Selective Laser Sintering (metals)	EOS Renishaw	Various alloys including aluminium, cobalt chrome, maranging steel, nickel, stainless steel, titanium
		Selective Laser Melting	ReaLizer	Various alloys including cobalt chrome, titanium, steel
		Electron Beam Melting	ARCAM	Various alloys including cobalt chrome, inconel, titanium
		LaserCUSING	Concept Laser	Various alloys including cobalt chrome, aluminium, titanium, bronze, nickel
Sheet Lamination	Sheets of material are bonded to form an object	Laminated Object Manufacturing	MCOR EnvisionTEC	Sheet paper Various composite thermoplastics
Vat Photopolymerization	Liquid photopolymer is selectively cured by light activated polymerization	Digital Light Processing	EnvisionTEC	Various epoxy and nano-composite resins
		Stereolithography	3D Systems	

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