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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.

Keywords

Additive Manufacturing

Direct Digital Manufacturing

Manufacturing Systems

Highlights

1. Provides a first evaluation of Industrial AM from the manufacturing systems perspective.
2. Demonstrates the application of Industrial AM Systems in the context of fourteen cases studies that are developed with four leading companies.
3. Establishes the role of multiple system resources that have traditionally been overlooked in Additive Manufacturing research.
4. Identifies opportunities to improve the competitiveness of Industrial AM by taking a systems perspective.

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, 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.

<table>
<tr><th>Process Type</th><th>Process Description (from ISO 17296-1)</th><th>Focal AM Technologies</th><th>Principal Manufacturers</th><th>Principal Materials</th></tr>
<tr><td rowspan="2">Binder Jetting</td><td rowspan="2">Liquid bonding agent is selectively deposited to join powder materials</td><td rowspan="2">3D Printing (3DP)</td><td>Z-CORP
3D Systems</td><td>Various powers including plasters, sands, and composite materials.</td></tr>
<tr><td>ExONE</td><td>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.</td></tr>
<tr><td rowspan="2">Direct Energy Deposition</td><td rowspan="2">Focused thermal energy is used to fuse materials by melting as they are being deposited</td><td rowspan="2">Laser Cladding
Laser Metal Fusion
Laser Metal Deposition</td><td>Trumpf</td><td>Various metal powders including stainless steel, cobalt, aluminium, and copper</td></tr>
<tr><td>Optomec</td><td>Titanium, nickel, tool steels, stainless steel, cobalt, aluminium, copper, and various composites</td></tr>
<tr><td>Material Extrusion</td><td>Material is selectively dispensed through a nozzle or orifice</td><td>Fused Deposition Modelling</td><td>Stratasys</td><td>Various thermoplastics including acrylonitrile butadiene styrene (ABS), acrylic-styrene-acrylonitrile (ASA), polyamide, polycarbonate, polypropylene</td></tr>
<tr><td rowspan="2">Material Jetting</td><td rowspan="2">Droplets of build material are selectively deposited</td><td rowspan="2">Multijet Modelling</td><td>Stratasys</td><td rowspan="2">Ceramics, liquid photopolymers, melted waxes</td></tr>
<tr><td>3D Systems</td></tr>
<tr><td rowspan="5">Powder Bed Fusion</td><td rowspan="5">Thermal energy selectively fuses regions of a powder bed</td><td>Selective Laser Sintering (plastics)</td><td>EOS
3D Systems</td><td>Polyamide, polyaryletherketone, polystyrene, and various composites</td></tr>
<tr><td>Selective Laser Sintering (metals)</td><td>EOS
Renishaw</td><td>Various alloys including aluminium, cobalt chrome, maranging steel, nickel, stainless steel, titanium</td></tr>
<tr><td>Selective Laser Melting</td><td>ReaLizer</td><td>Various alloys including cobalt chrome, titanium, steel</td></tr>
<tr><td>Electron Beam Melting</td><td>ARCAM</td><td>Various alloys including cobalt chrome, inconel, titanium</td></tr>
<tr><td>LaserCUSING</td><td>Concept Laser</td><td>Various alloys including cobalt chrome, aluminium, titanium, bronze, nickel</td></tr>
<tr><td rowspan="2">Sheet Lamination</td><td rowspan="2">Sheets of material are bonded to form an object</td><td rowspan="2">Laminated Object Manufacturing</td><td>MCOR</td><td>Sheet paper</td></tr>
<tr><td>EnvisionTEC</td><td>Various composite thermoplastics</td></tr>
<tr><td rowspan="2">Vat Photopolymer-ization</td><td rowspan="2">Liquid photopolymer is selectively cured by light activated polymerization</td><td>Digital Light Processing</td><td>EnvisionTEC</td><td rowspan="2">Various epoxy and nano-composite resins</td></tr>
<tr><td>Stereolithography</td><td>3D Systems</td></tr>
</table>

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

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 its parts [31]. A system's performance is critically dependent on the effectiveness of each of the component parts to work together, not the independent performance of each [13]. Understanding the nature of manufacturing systems therefore requires an appreciation of how the component parts achieve assemblage to the whole, rather than an emphasis on focal manufacturing technologies.

2.2 A manufacturing systems perspective for Additive Manufacturing

Reviewing the literature identified a dearth of AM research from the systems perspective, with most studies employing the 'system' term typically referring only to the individual AM machine 'system of parts' in operation [e.g. 32, 33], as an aggregate collection of technologies [e.g. 34, 35], or as individual components of traditional factory-based mass production systems [e.g. 36]. Each of these applications of the 'system' term successively broadens what resources AM systems may include, but lacks specificity and linkage to systems theory.

One notable study that has taken a more systems-orientated approach is Kim et al. [37], who have focused on AM information system. In this conceptual study they identify information requirements through the AM workflow, and propose a supporting *information systems* architecture. Whilst this work does not focus on the physical transformative activities undertaken in *manufacturing* systems that are the focus of the current study, it does provide a useful insight into the information resources needed in support of AM production additional to the 3D CAD model that is typically espoused in literature.

The use of the term 'system' for AM is therefore often pleonastic, and to-date there has been no formalization of the AM system concept from a manufacturing perspective. As a result, the richer contribution that can be gained for manufacturing adopting a systems perspective [16] has largely been overlooked in current research. To adopt a manufacturing systems perspective, it is necessary to understand what the components of the system are, and the boundaries between these. Notably from a process perspective there has been some consideration of generic process chains for AM [e.g. 1], however these treat AM as an aggregate collection of resources, rather than exploring integrated whole promoted in systems research. However, whilst there has been little research focus that adheres to the theoretical definition of a manufacturing system, several authors have identified implementation frameworks are helpful to understand potential boundaries and components for the system. A broad, but useful perspective on system boundaries is offered by Birtchnell and Urry [38] who identify that a triad of systems need to be considered for Additive Manufacturing: the production system, the distribution system, and the consumption system. A more focused work by Nagel and Liou [39] proposed that the manufacturing system is comprised of five key components: production planning (software), control, motion, unit manufacturing process, and a finishing process. Similarly, in the development of an implementation framework, Mellor et al. [40] defined 'systems of operations', which identified the activities of design, process planning, quality control, cost accounting, and systems integration as relevant to systems concepts. Whilst none of these draw on manufacturing systems theory per se, they do help to understand some components that might be included in a formal definition of a manufacturing system.

It is essential that manufacturing systems are controlled [41], but it is noticeable that emphasis on the control of AM is extremely limited in the published research. Of the little research available, most focuses on the control of AM machine processes (i.e. motor controllers and getting feedback from the machines). At the system level, control architectures have not been formally considered, though effectively either centralized or decentralized approaches are apparent in the literature. For example, in centralized architectures Nagel and Liou [39] focused on control from the perspective of electrical or mechanical control technologies, whilst Espalin et al. [33] highlighted the use of reconfigurable real-time controllers to operate the system, and the role for both hardware and software to support control objectives using finite state machines. For decentralized architectures control has focused on Internet-based 'tele-control', allowing the operations of Additive Manufacturing machines remote from their location [42].

In summary, as a result of the literature reviews in Sections 2.1 and 2.2 it can be identified that whilst the benefits of a systems approach to manufacturing systems are well-established for manufacturing in general, such knowledge does not extend to AM. Existing research often uses the 'system' terminology, but has not clearly identified what this means in practice. By evaluating the available literature, Section 2.2 has explored some current interpretations of system components, system controls, and information requirements in an AM context, however it is identified that there has been no detailed investigation on the fundamental nature of AM systems based on empirical evidence. This is a notable omission: AM is typically celebrated by researchers in terms of the unique capabilities it can bring to manufacturing, and manufacturing systems perspectives have been identified as optimal for solving manufacturing problems [22]. In this study we address this important research gap through the detailed investigation that is described in the next section.

3 Research Method

3.1 Data collection

Given the overall paucity of knowledge considering AM from the systems perspective, this study employs case studies to understand contemporary phenomena within real-life situations [43]. The unit of analysis is a value stream (which is linked to a product rather than a firm) and, to support generalizability of the cases, fourteen distinct case studies (Table 2) were examined. This range of products is an important consideration, since manufacturing systems are typically configured to support the products that they are to produce. The study involved four well-established Industrial AM companies (Table 3) with operations in the UK, Europe, and US. Such use of a multi-site study is particularly useful to compare how different firms employ AM, and to understand commonalities and differences between the operations. The research was informed by 22 interviews with managers and technicians, using a semi-structured approach to enable focus on pertinent topics, but with the flexibility to explore emergent and unanticipated findings. Additionally, observations were undertaken of the manufacturing systems in operation to identify the practical realities of the operations first-hand, and to see events as they arose, rather than through post-rationalized interviews. To support this research additional data was obtained through interviews with customers of the focal AM companies, together with archival data from company documents.

3.2 Data analysis

Evaluation of the manufacturing systems was achieved through three distinct stages. In stage 1 a detailed review of all activities taking place in the manufacturing system was undertaken. For each activity, the main enabling mechanisms were identified, and the methods by which the activity was controlled was recorded. IDEF0 diagrams were drawn for each case, and tables of activities, methods, and controls were constructed to aid cross-case comparison. An example IDEF0 diagram and data-table is provided in the appendices. The use of IDEF0 diagramming was employed as it is a well-established [44-46] and efficient systems analysis method that can identify both data and control through its diagrammatic approach [47], combining graphical and natural languages to form a co-ordinated set of diagrams [48].

In stage 2, logical boundaries were identified to classify the components of an IAMS. IDEF0 diagrams are particularly useful in the establishment of definite system boundaries [48], and together with the tabulation of results it was possible to identify four general system components common to all cases.

In stage 3, the structure of the IAMS was identified to delimit the system from its external environment. This stage links the generic manufacturing system proposed by Parnaby and Towill [16] with the empirical data collected in this study to understand system inputs, outputs, disturbances, and controls.

Case No.	Additive Mfr	Product Description	AM Application	Volume (annual)	Variety/ Customization	Design source	Production leadtime
1	A	In-The-Ear (ITE) Hearing Aid	Rapid Manufacturing	Tens of thousands	High	Reverse Engineered	1 day
2	B	Replica timbers used in the creation of a model medieval ship	Rapid Manufacturing	700 (in 10 batches)	High	Reverse Engineered	2 weeks / batch
3	B	Scale models of ancient stone monuments	Rapid Manufacturing	4	High	Reverse Engineered	2 weeks
4	B	Architectural scale models of complex shaped buildings	Rapid Manufacturing	20	High	Human Design	1 week
5	B	Hydroform tool inserts to be used in the production of exhaust systems	Rapid Tooling	1	High	Reverse Engineered	2 weeks
6	B	Inspection fixture for prototype toothbrush	Rapid Prototyping	1	High	Human Design	1 week
7	B	Functional prototype of an exhaust sensor tool	Rapid Prototyping	3	High	Human Design	1 week
8	C	Customized surgical guide	Rapid Manufacturing	Tens of thousands	High	Reverse Engineered	3 weeks
9	C	Customized lighting product designed by customer via website	Rapid Manufacturing	Hundreds	Medium	Catalogue Design	1 – 2 weeks
10	C	Standardized lighting product designed by professional designer	Rapid Manufacturing	Hundreds - thousands	Low	Online Configurator	2 weeks
11	C	Hybrid fixture system customized for user application	Rapid Manufacturing	Hundreds - thousands	Medium	Reverse Engineered	3 days
12	C	Designer furniture	Rapid Manufacturing	1	High	Human Design	1 week
13	D	Aesthetic Marketing Model (Headphones)	Rapid Prototyping	9	High	Human Design	1 – 2 weeks
14	D	Automotive Component	Rapid Tooling	3	Low	Human Design	1 – 2 weeks

Table 2: Case summaries

Company	**A**	**B**	**C**	**D**
Employees	150	5	1000	5
Operating Region	Europe	UK	Worldwide	Europe
Ownership	Private	Private	Private	Private
Years using Additive Manufacturing	>15	>20	>25	>20
Focal Market(s)	B2B Audiology and hearing aid products	B2B Industrial prototyping Concept designs Low-volume & customized products	B2B & B2C Industrial prototyping Concept designs Specialist medical Specialist industrial Consumer products	B2B Industrial prototyping Concept designs Specialist medical Specialist industrial Consumer products

Table 3: Company profiles

4. Results

4.1 Stage 1: Identifying activities, enabling mechanisms, and control for an Industrial AM System

4.1.1 Activities

Analysis of the case data identified 36 principal activities undertaken in the fulfilment of demand for the various different products being produced (appendix B). Through tabulation it was possible to identify ten activities integral to the manufacturing system that were always performed regardless of the product being produced or AM technology being employed. Several activities were shown to be process specific, but achieving a similar outcome (e.g. sintering for LS, photocuring for SLA both serve to produce a part). Other activities were product-specific (e.g. undertaking scanning activities where an existing artefact could be used versus creating a new design idea from scratch). Choices made in the means of design elicitation had the most notable effect on the activities conducted; where designs were achieved by reverse engineering of an existing artefact, scanning and subsequent quality assessment of data were necessary, whereas original design required more emphasis on initial design development and 3D CAD modelling.

4.1.2 Mechanisms

For every activity identified in each case, an assessment was made of the mechanism by which it was achieved. In the manufacture of each different item a plethora of resources was involved, and consistent with Parnaby [15] three general categories were identified: labour, machine, and information processing resources. Although many studies have identified that AM enables the fabrication of parts without the need for traditional enabling mechanisms such as labour [49], human involvement was evidenced in the majority of activities undertaken in the manufacturing system. Further, whilst it has been suggested that Additive Manufacturing is “zero skill manufacturing” [50], in practice we found only evidence for either skilled or semi-skilled workers engaged in these activities. These workers utilized a range of machine resources to achieve their objectives, including automated (e.g. ovens), semi-automated (e.g. optical scanning tools), and manual (e.g. hand tools) resources. Interview respondents for all companies identified that the need for some degree of skill in labour precluded the use of generic staff sourced from recruitment agencies, highlighting the importance of their abilities for AM. Extensive utilization of information processing resources was made, which was delimited in terms of process specific software (e.g. for preparation of AM 3D files), product-specific software (e.g. for configuration of a specific type of product), general software (e.g. spreadsheets for planning), and physical documents passed through the system (e.g. work orders).

4.1.3 Controls

Activities that are enabled by their mechanisms also need controls which guide or regulate the individual activity as it is undertaken, and these can be wide-ranging, including organizational policies and environmental influences [51]. Five principal controls and their typical nature can be identified from the cases:

1. Product design controls. These are mainly *product*-specific, and may reflect industry norms concerning the approach to be taken in the design. For example, in the design of an architectural part (Case 4), conventions for aesthetic and mechanical properties are well-established and applied in design. Similarly, in the development of custom fixtures (Case 11), standard interfaces to connect parts together are essential, and design controls exist for these. AM has been acknowledged to remove many constraints concerning 'Design For Manufacturing' [52] which support this observation.
2. Preparatory controls. These are typically *process*-specific, and concern the application of established procedures to achieve requisite part performance in manufacture. For example, controls exist to promote accuracy in the production process in the layout and orientation of parts within a build chamber. Much research has explored the various options to achieve optimal preparation of parts for manufacture (e.g. [53, 54] and although the different manufacturers have their own approaches in the execution of these controls, in general commonality exists for each process.
3. Controls in manufacturing. These are mainly *process*-specific attributes of individual manufacturing machines, and are intended to ensure that the manufacturing process achieves its requirements. For the 14 cases, the controls observed related to the focal machines, and were instigated by the machine manufacturers.
4. Controls in post-manufacture processing. These combine both *product* and *process* specificity, for which the purpose is to prepare the manufactured part for finishing activities. For example, process-specific controls for Laser Sintered parts concern effective material recovery for recycling. Product-specific controls are typically associated with post-manufacturing operations involving cleaning and finishing, where the individual products have specific requirements to be observed.
5. Controls in assembly and testing. These are mainly *product* specific, and exist to finish a part to meet the requirements of the customer.

4.2 Stage 2: Identifying the components of an Industrial AM System

Stage 1 provided a detailed understanding of the way in which manufacturing was achieved for each of the 14 cases; however, this is both product and process specific. In order to extend these findings to provide a general understanding of the principal components of an IAMS, cross-case assessments were performed using the IDEF0 diagrams and data tables, leading to the identification of four distinctly-bounded system components. These four components are explored in this section, with supporting evidence drawn from examples observed in the individual cases.

System Component 1: Design

Design in IAMS represents all activities from the inception of the original idea, through to the creation of an initial 3D design file. Designs may be created from scratch using 3D CAD software (e.g. new architectural designs in case 4), reverse engineered by scanning an existing artefact (e.g. by scanning archaeological artefacts in cases 2 and 3), or derived from an existing design using configurator software to provide a customized design (e.g. by choosing feature options in the design of a table lamp in case 9). Often designs are prototyped with the customer either virtually (on-screen), or through a physical prototype (e.g. by providing a sample product for the customer in case 7). Some cases employ multiple options (e.g. scanning and confirmation in the hearing aids of case 1). The achievement of design can draw solely on employees of the company, or can involve the customer within the manufacturing system. Customer engagement in design promotes product customization, and the use of AM as part of a co-design or co-creation strategy has been widely discussed [55]. In practice, such engagement with the customer necessitates appropriate information channels for the communication of design and order details.

System Component 2: Pre-processing

In contrast to many studies that identify the ability to fabricate directly from a 3D design file [e.g. 12], this study demonstrates the need for many preparatory activities to be undertaken. Interview respondents from all four companies emphasised a range of activities being undertaken in preparation for manufacturing, and these are identified within this component of the system. These pre-processing activities include manufacturing feasibility evaluations, error checking, build preparation (collection of multiple files for simultaneous manufacture), and production planning activities in which resources of the system are allocated to work. Most of the cases demonstrated these pre-processing activities to be both time consuming and labour intensive, particularly where attributes of the product needed exploration before processing parameters could be determined. For example, in Case 2 trials of process parameters were needed in order to ensure accuracy requirements were met, necessitating more than a full day of labour and machine resources. However, some automation of processes was shown to be feasible where production volumes justified development of software tools to lessen the labour element of the work. For example, in Cases 1 and 9, dedicated software was used to automate much of the optimization and quality evaluation operations necessary in the preparation of the electronic design file. These products are comparatively high volume (for AM production), are expected to have a long life-cycle, and are amenable to some automation, making them suitable candidates for investment in software tools.

Systems Component 3: Manufacture

This component concerns the physical production of the part(s) by the Industrial AM machine using the output of the previous two system components. Each time the machine is used a machine-specific setup is required, involving the preparation and loading of materials, and this was common for all cases. Whilst the activities of machine setup are seldom mentioned in literature, they remain a very manual activity, with labour employed in the physical cleaning and loading of materials. This is an important issue for industrial machines, where the total weight of materials loaded (by hand) into a machine is significant. Setups can also require build-specific configurations to be applied for certain types of product; this takes time and labour effort and may introduce inconsistencies in product quality. Where product volumes suffice, and where the firms are sufficiently large to accommodate multiple instances of the same machine type it is commonplace to dedicate specific machines to specific material/configuration combinations (Cases 1 and 8) to avoid major changeovers.

System Component 4: Post-processing

None of the 14 cases evidenced the ability of AM machines to produce finished products without further work required before completion. Therefore, the final component of the manufacturing system is post-processing, which encompasses all the finishing activities, including product identification (in multi-product builds), product cleaning and finishing, material recovery for recycling, quality inspection, and appropriate assembly of multi-component products. All of these activities required semi-skilled or skilled labour, and drew extensively on the use of 'conventional' manufacturing tools such as brushes, air dusters, measures, and ovens in order to complete the part to the customer's requirement.

4.3. Stage 3: Identifying the structure of an Industrial AM System

Each of the generalized system components represents a combination of similar activities, mechanisms, and controls that have been demonstrated in each of the 14 case studies. These findings are combined with the existing theoretical positions identified for conventional manufacturing systems [15, 16, 24] to propose the general concept of an Industrial AM System (Figure 1). As a manufacturing system, IAMS promotes consideration of the 'whole' whilst acknowledging the contribution of each of the four component 'parts', together with the activities, enabling mechanisms, and controls within these. In doing so, it aligns to the top-down input-transformation-output perspective [15, 56], and is comprised of component subsystems that facilitate focus at different parts of the system [57]. In terms of their environment, it is identified that manufacturing systems exist within organizations, and there is integration of information and control between the manufacturing system and the company within which it operates [26]. An IAMS therefore exists within an internal environment (the focal organization or factory), as well as the wider external environment (upstream and downstream in the supply chain).

By considering manufacturing from the system perspective, rather than individual machine level, opportunities exist to better manage the provision of Additive Manufacturing. All manufacturing serves to fulfil demand requirements, and as shown in Figure 1 this is consistent for an IAMS (either as internal demand from the manufacturer, or to satisfy an external customer requirements). To satisfy this demand, a multitude of different resources are engaged (including people, equipment, information processing), to perform activities for each of the system components. In practice, many of these resources will be shared between different activities to maximise their utilisation, and minimise their cost. By taking a systems perspective, managers can plan the allocation of these resources in the achievement of production requirements, and choose optimal solutions for the whole system, rather than an individual AM process.

The systems perspective also provides a useful approach to the evaluation of disturbances to production, and this can be in demand (either as uncertainties as to what is required, or fluctuations in terms of volumes required), or in the manufacturing process (for example in labour absenteeism or machine breakdown). These types of problem were frequently noted by research participants, who often had poor visibility of future demand, difficulties with machine reliability (compared to conventional technologies), but still needed to achieve high machine utilization and quick response production to remain competitive. The systems perspective to disturbances allows managers to appreciate negative effects across the whole production system, and marshal and control resources in mitigation of this.

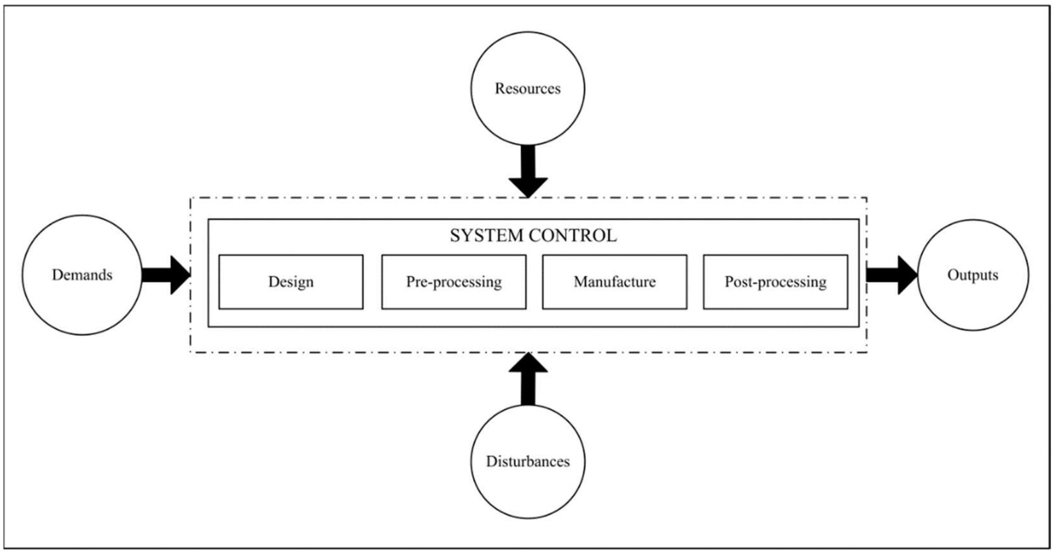


Figure 1: The concept of an Industrial AM System

5. Discussion

The need for modern manufacturers to achieve competitiveness in their operations is well known, and this requires that managers are able to fully optimise every aspect of their operations. Whilst Additive Manufacturing technologies have the potential to yield major benefits in production [58], focusing solely on machines will not produce the fully-optimised production facility that is needed today. By adopting the systems perspective, this research makes an important contribution in extending consideration of Additive Manufacturing beyond the capabilities of individual machines, to a holistic evaluation of the activities, enabling mechanisms, and controls that actually combine to achieve production requirements. Such an approach offers the potential for companies to make improvements throughout the whole operations, and in Table 4 an overview of these is provided in terms of the traditional strategic objectives for manufacturing [25].

5.1 Cost

Current research has placed most emphasis on the ability to minimise the operational cost of Additive Manufacturing in terms of machine operations (i.e. for the IAMS Manufacture component). However, there has been scant research to explore the costs experienced in the other components identified in IAMS. For example, whilst design is well established as being a challenging activity for AM [52], current AM cost models seldom incorporate this in their evaluations. Neither are the decision-intensive activities in pre-processing or the labour-intensive post-processing activities considered in detail, yet without them AM parts could not be achieved. In this study we noted several examples where manufacturers actively targeted these costs (e.g. reducing labour in design using software configurators in cases 1, 8, 9, and 11), and these have the potential to significantly improve the competitiveness of Additive Manufacturing operations. Understanding the full-system cost is therefore essential to fully appreciate the competitiveness of the operations, and to make decisions to improve these.

5.2 Quality

Extensive research has focused on the improvement of quality in Additive Manufacturing, and this has typically focused on aesthetic (e.g. improving surface finishes), or functional considerations (e.g. improving longevity of parts) that can be achieved by machines. Quality in the final delivered product is achieved as a culmination of all activities performed on the part, and considering other aspects of IAMS is essential for improving quality overall. In practice, this requires a linkage in improvements in design and preparatory activities with the physical production and post-processing. For Case 2 this was particularly evident, and interviewees explained how initial planning of their AM products involved extensive consideration of activities from design through to post-processing. Given the inter-relationship between decisions at different stages of production and the quality of the final part, a systems perspective helps to align these for the achievement of optimal quality.

5.3 Speed

The ability to produce parts quickly (relative to some conventional technologies) is often identified as a benefit of the technologies, yet time assessments typically focus on the direct production time in the machine. In terms of an IAMS, the speed objective extends all activities undertaken within the system, and so speed assessment is more realistically linked to the actual time taken to produce the part. This can have important consequences for production, as managers better understand delays and bottlenecks in their operations. For example, in Case 1, the repetitive nature of production allowed the focal company to understand the duration of each activity, and to reconfigure labour to effectively tackle bottlenecks to expedite overall production through the system, rather than focusing on individual processes.

5.4 Dependability

The dependability of an operation concerns its ability to deliver products on-time and of the correct quality. Few studies explicitly consider dependability in AM, and instead the emphasis is typically on the reliability of machine. Early AM technologies suffered with reliability issues, and 'failed builds' were commonplace; this therefore had negative consequences for the other strategic objectives of the operations. In an IAMS, dependability concerns the ability for every system component to effectively achieve its objective, since the failure of any part of the system will degrade overall performance. As an example, the architectural models produced in case 4 highlight this problem well; some were delayed in design (leading to delayed production), some were misconfigured in pre-processing (leading to the wrong size parts subsequently being produced), and some were damaged in post-processing (necessitating repair). For managers looking to evaluate Additive Manufacturing's dependability, focusing only on the manufacturing stages risks overlooking many other potential areas for concern, supporting a systems perspective.

5.5 Flexibility

Flexibility is often central to an organization's competitive strategy [59], and it can be employed either in response to changing circumstances, or proactively in anticipation of future change [60]. Additive Manufacturing is often termed as being flexible, and whilst different authors have different interpretations on what 'flexibility' is, most link it to the capabilities of the individual machines, rather than other aspects considered within an IAMS [61]. Most commonly flexibility is considered in terms of the ability to produce 'on-demand' [62], to create a wide range of different parts [63], or to produce complex geometry parts [64]. However, as shown in this current study, a wide range of different activities and enabling mechanisms are inherent in AM production, and these need to be effectively controlled. Flexibility within an IAMS concerns how the resources of each system component can be leveraged to ensure that the whole system can flex to satisfy demand appropriately. In Case 1, this was particularly evident in terms of labour, which was dynamically reallocated to provide additional resource in response to capacity constraints. This was shown to improve system throughput by making better use of resources, without increasing overall production costs.

		Definition	Current Research Perspectives		Notable Implications of a Systems Perspective
			Current Approaches	Identified Limitations	
Competitive Objectives for Manufacturing	Cost	The expense incurred by manufacturing operations in the satisfaction of demand.	Emphasize AM machine operation costs (based on time utilized), together with general labour costs and some factory overheads.	Incomplete understanding of some direct production costs, particularly where resources are shared between the manufacture of multiple products.	Full costing of all system resources used in the satisfaction of demand, with increased specificity in labour rates relative to skill levels and improved understanding of non-AM machine resource costs.
	Dependability	The correct satisfaction of demand at the expedited time.	Little explicit focus in literature; typically concerns issues of AM machine reliability.	On-time satisfaction of demand is reliant on all parts of production; focusing only on AM machines will not address problems elsewhere in manufacturing.	Every resource that contributes to the fulfilment of demand is considered to ensure that dependability is achieved.
	Flexibility	The ability to change attributes of the production system and/or its outputs with little penalty.	Largely focused on AM machine capability to produce products on-demand, customized products, or a range of different products.	Flexible manufacturing requires all system components to be flexible, not just individual AM machine processes.	Flexibility is considered for all system resources, allowing the design of manufacturing systems that can exploit the flexibilities of each resource.
	Quality	The manufacture of products that conform to a predetermined specification.	Emphasis on improvement of AM machine and material capabilities to achieve part qualities.	Quality processes are needed throughout production, yet research typically focuses only on AM machine capabilities.	Emphasis on quality from the systems perspective supports overall quality improvement through complimentary activities in all production activities.
	Speed	The time taken to respond to customer demand.	Typically considers the speed at which parts can be produced by an AM machine.	Very little emphasis on the often-significant time taken in design, pre-processing, and post-processing.	Enables a better understanding of product lead-times (rather than AM part fabrication times), which can be used to improve production planning and customer satisfaction.

Table 4: Research perspectives on AM implications for manufacturing's competitive objectives

6. Conclusion

Manufacturing makes an important contribution to the prosperity of national economies, and the technologies of Additive Manufacturing have the potential to make a significant impact in a range of application sectors. What is crucial for research and practice alike is that the advantages of AM can be appropriately leveraged for optimum benefit, and in this study we make a contribution to this objective by exploring how the well-regarded systems approach can be employed for these unique technologies.

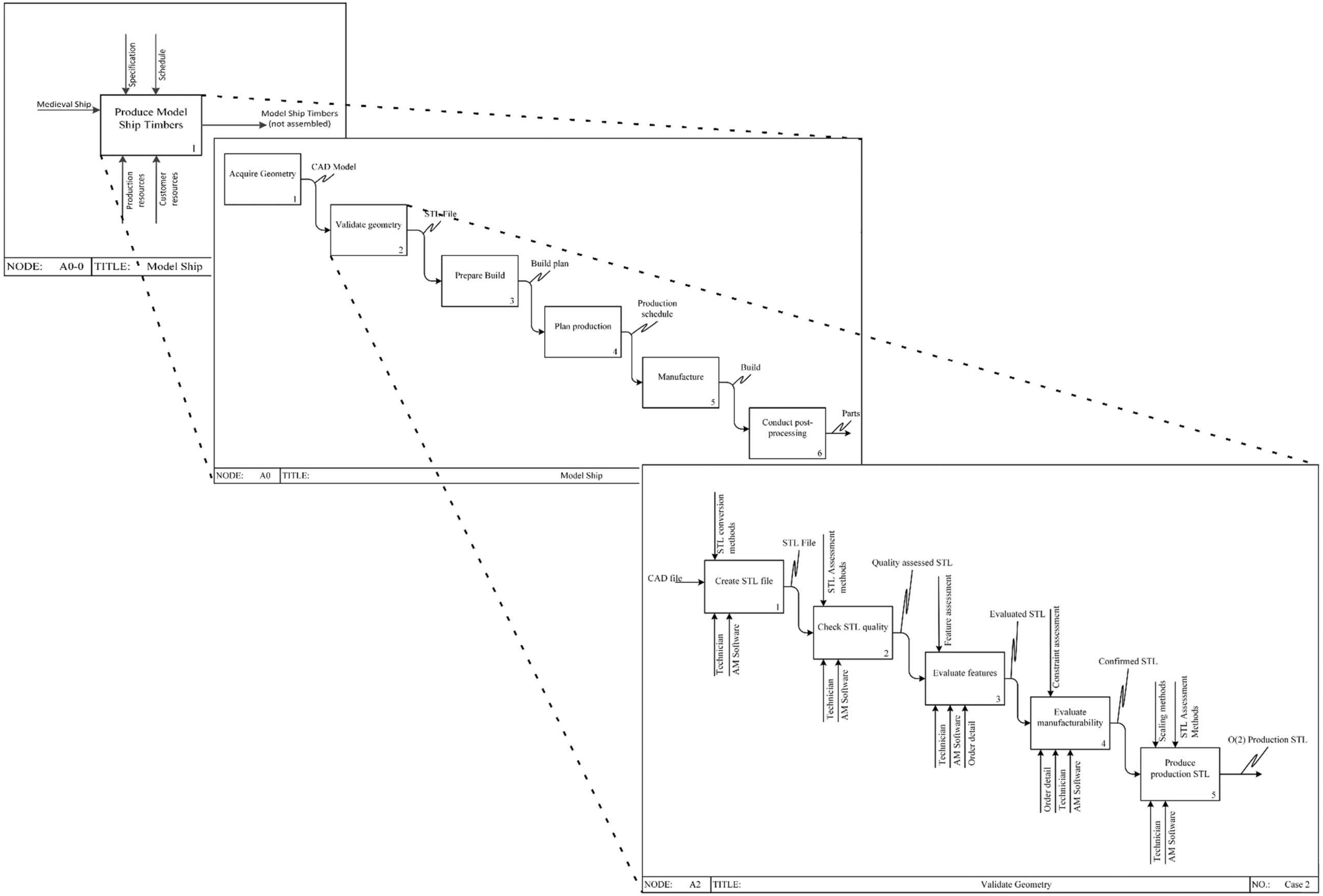
The literature review highlighted that whilst systems perspectives are well-established for general manufacturing, in terms of AM there has been very little specificity in research discussions. To provide redress for this research gap, this study has considered the operations at four industrial Additive Manufacturing companies in the production of fourteen different products. Although the case studies vary significantly in the production volumes, AM technologies employed, and intended product applications (RP, RT, RM), our analysis highlighted many commonalities that can be used in the development of a general understanding of IAMS. Building on the established theory for manufacturing systems [15, 16] with this industry data, we propose an empirically informed concept for IAMS. Through this we show four distinct system components, and detail the various activities, mechanisms, and controls through which production may be realized. This approach therefore provides more specificity about the nature of AM systems than has been identified in existing literature, building on sound theoretical systems principles with a considerable volume of industry data.

The systems approach allows researchers and practitioners to focus on problems of the complexity that is realistic in contemporary manufacturing environments. Whilst much research has examined the technical operation of AM machines and materials, we identify that a systems perspective encompasses a multitude of attributes that need to be considered as AM technologies are employed in competitive manufacturing environments. Linking AM systems to the strategic objectives of manufacturing, we emphasise the gap between current machine-based research, and the opportunities afforded by a systems viewpoint.

As this is an initial study that bridges systems theory and industrial practice, we note there are many opportunities for future research to exploit and extend this work. We believe that the systems perspective offers much opportunity for a fuller understanding of the applications and implications of AM, and encourage further studies to adopt this approach. We suggest that such a transition in research towards considering AM as a system, rather than a machine is also likely to yield significant benefit for industrial practice, since scholarly outputs will more closely align with the realities observed in manufacturing practice.

Appendix A: Example IDEF0 extract

IDEF0 diagramming conventions [65] dictate that no more than six activities (or functions) are included within a single diagram. A top-level context diagram provides (A-0) an overview of the subject of the model, with subsequent child diagrams providing increasing levels of detail on individual activities. In this study multi-level diagrams were constructed for each of the case studies, and in Figure 1 an extract from the model ship example (Case 2) is provided.



Appendix B: Summary activity analysis

		Case Reference													
	Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Design	Create design idea				■			■		■			■	■	■
	Select item to scan	■	■	■		■			■						
	Prepare item for scanning	■	■	■		■			■			■			
	Scan item	■	■	■		■			■			■			
	Review pointcloud		■	■		■			■			■			
	Inverse existing CAD design						■								
	Create 3D CAD model	■	■	■	■	■	■	■	■	■		■	■	■	■
	Conduct Virtual Prototyping			■	■			■	■				■		
	Conduct Physical Prototyping		■	■	■			■						■	■
	Design optimization	■						■	■			■		■	■
Pre-processing	Prepare STL file	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Check STL file quality	■	■	■	■	■	■	■	■	■		■	■	■	■
	Evaluate part manufacturability		■	■	■	■	■	■	■			■	■	■	■
	Evaluate feature manufacturability		■	■	■	■	■	■	■			■	■	■	■
	Prepare final production STL	■	■	■	■	■	■	■	■	■		■	■	■	■
	Batch STLs for simultaneous production	■	■		■	■	■	■	■	■	■	■	■	■	■
	Identify accuracy requirements		■	■	■	■	■	■				■	■	■	■
	Configure build layout	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Determine optimal build parameters		■	■	■	■	■	■	■	■	■	■	■	■	■
	Finalize build configuration	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Identify production capacity	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Identify production priorities	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Produce production plan	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Manufacturing	Perform machine setup	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Photocure resin	■									■			■	■
	Laser Sinter powder		■	■	■	■	■	■	■	■	■	■	■		
	Drain build	■									■			■	■
	Cool build		■	■	■	■	■	■	■	■	■	■	■		
Post-processing	Disassemble build & material recovery	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Remove excess powder / Clean	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Perform oven processing					■								■	■
	Perform quality assessment	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Perform part collation / ordering		■		■				■				■		
	Perform part colouring										■	■	■		
	Assemble parts	■				■	■	■		■	■	■	■	■	■
	Additional processing					■									

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