The impact of Additive Manufacturing on the Product-Process Matrix

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Abstract

The relationship between volume, variety, and process choice is a fundamental tenet of manufacturing research and practice, and through the product-process matrix managers balance trade-offs between the traditionally dichotomous objectives of flexibility and cost in process selection. In this paper we examine the adherence of Additive Manufacturing systems to traditional trade-offs, and identify circumstances where they deviate from these established norms.

Using engineering philosophy we develop an extension of the product-process matrix to accommodate both variety and customization measures, which is used to evaluate case study research conducted with five major Additive Manufacturing companies. Fifteen case studies inform the research, drawn from a broad range of industry sectors. A qualitative approach was taken, using semi-structured interviews and process observation.

The study demonstrates that Additive Manufacturing systems can support both alignment and disjunction to established theory. For many cases a general conformance to the traditional product-process matrix 'diagonal' is evidenced. However, several cases show significant deviation, demonstrating the achievement of both variety and volume for both batch and line production. Through a detailed exploration of the focal cases, we highlight the characteristics of both products and Additive Manufacturing systems that can help overcome traditional trade-off constraints.

Keywords: Manufacturing Strategy, Flexibility, Trade-offs, Customization, Engineer-To-Order, Additive Manufacturing

Highlights

- Extends the strategically important concept of the Product Process Matrix to accommodate both variety and customization measures.
- Uses empirical data gained from five commercial Additive Manufacturing companies to examine the implications for the Product Process Matrix.
- Examines characteristics of Additive Manufacturing and its products that support alignment and divergence from established theory.

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1. Introduction

The ongoing 'digitization' of manufacturing has seen a succession of technologies contribute to the transformation of manufacturing operations. One of the principal approaches being employed in contemporary Digital Manufacturing is 'Additive Manufacturing' (sometimes termed '3D printing'), whereby parts are produced directly from 3D model data through the incremental joining of material layers (BSI 2014). Building on significant growth since its inception in the mid-1980's, Additive Manufacturing has been shown to offer significant opportunities in a range of applications, including medical devices (Yan et al. 2018; Culmone, Smit, and Breedveld 2019) and aerospace products (Najmon, Raeisi, and Tovar 2019; Liu et al. 2017). In the last decade the expiry of key technological patents has led to increased interest in lower-cost Additive Manufacturing machines for domestic applications (Ryan et al. 2017), however industrial machines still dominate the overall value of the Additive Manufacturing industry, which by 2024 is expected to be worth $35.6bn (Wohlers 2019).

Various studies have shown that Additive Manufacturing is often able to economically compete with conventional manufacturing approaches (Ruffo, Tuck, and Hague 2006; Tuck et al. 2008; Baumers et al. 2017). This capability, together with others such as increased customer-engagement in manufacturing (Piller, Weller, and Kleer 2015), and opportunities for a redistribution of manufacturing (Roscoe and Blome 2019; Wagner and Walton 2016) and supply chain reconfiguration (Tziantopoulos et al. 2019) have led some authors to herald a 'revolution' in manufacturing (Economist 2012a; Huang et al. 2013; Simons 2018), with Additive Manufacturing identified as usurping many conventional manufacturing technologies.

Revolutions lead to dramatic change for operations, and so demand careful consideration of whether existing knowledge remains applicable in a changed world. The Industrial Revolutions of the 18th and 19th Centuries transformed approaches to manufacturing and its management (Sprague 2007), and in the 20th Century various advances, including the microchip and the internet, led to further significant changes (Gunasekaran and Ngai 2012). To be successful, manufacturers have needed to understand the benefits and challenges of new technologies and appreciate how best to embrace them within their operations.

Whether Additive Manufacturing will result in a comparable revolution for the 21st Century is uncertain, but it is expected to transform both operations and strategy (D'Aveni 2015, 2018). Even though there are currently many limitations of the Additive Manufacturing technologies (Shukla, Todorov, and Kapletia 2018), they are widely seen as potentially disruptive in the transformation towards Smart Factories and Industry 4.0 (Oesterreich and Teuteberg 2016; Li et al. 2018; Bibby and Dehe 2018). However, whilst there has been much research focusing on the technological advantages, there is comparatively little empirical research that explores the implications arising from Additive Manufacturing in practice (Fogliatto, da Silveira, and Borenstein 2012; Mellor, Hao, and Zhang 2014), and a general dearth of evidence-based strategic literature.

One long-standing staple of manufacturing theory that may be affected by Additive Manufacturing is the product-process matrix as originally defined by Hayes and Wheelwright (1979). This framework identifies four distinct process types, their typical attributes, and how they can be appropriately used to satisfy different combinations of volume and variety. In turn, this helps to balance flexibility to offer variety, with costs incurred because of lost efficiency. Central to the product-process matrix is a diagonal line of best-fit between process and product structures to balance cost trade-offs, and this thinking has been incorporated into classic manufacturing strategy text books and more general debates around the theory and practice of manufacturing strategy (Fine and Hax 1985; Johansson and Olhager 2006; Slack and Brandon-Jones 2018; Olhager and Wikner 2000).

Since inception of the product-process matrix over 40 years ago, operations and the study of operations management has changed quite markedly. New production and information technologies have affected many aspects of the production environment, which in turn influences the nature of trade-offs (Skinner 1992). Services, and service operations have gained significant research interest since the 1980s, building heavily on the tools and techniques of traditional product-focused operations management (Johnston 1999). As the operating context has changed, research has extended the principles of the product-process matrix for production (e.g. Ahmad and Schroeder 2002; Hullova, Trott, and Simms 2016), services (e.g. Schmenner 1986; Wemmerlöv 1990; Silvestro et al. 1992; Collier and Meyer 1998; Buzacott 2000), and combined product-service offerings (e.g. Johansson and Olhager 2004, 2006). Nevertheless, the fundamental tents of the original matrix are still very much applied in contemporary studies, with recent examples such as Helkiö and Tenhiälä (2013), Bello-Pintado, García Marco, and Zouaghi (2019), and Kumar et al. (2020) demonstrating the ongoing relevance of the tool from the perspective of manufacturing management.

It is possible that emerging Additive Manufacturing technologies threaten some of the assumptions and foundations related to the trade-offs and configurations suggested by the product-process matrix (Khajavi et al. 2018; Khajavi, Partanen, and Holmström 2014; Eyers and Potter 2017). Whilst many earlier studies considered Additive Manufacturing for low-volume, customized production, more recently some examples suggest the potential of Additive Manufacturing to achieve a wide spectrum of production volumes, whilst attaining both high variety and customization in the products produced (e.g. Eyers and Dotchev 2010; van Noort 2012). This would conflict with the fundamental principles of the product-process matrix, where a single process type typically aligns to a particular volume/variety combination. If such a capability is possible in practice, then it has the potential to yield enormous competitive advantage for firms. In response to this observation, the aim of this paper is to explore whether Additive Manufacturing can overcome the traditional trade-offs inherent in the product-process matrix, and if so, under what circumstances?

In the conduct of this research we follow the guidance of Holmström and Romme (2012), who argue that when dealing with emergent technologies two activities are paramount. The first is a robust theoretical development, as provided in Section 2 that reviews existing literature and presents the theoretical underpinning for the work, which yields a maturation of the product-process matrix that incorporates engineering philosophy. The second activity requires the connection of this theory to practice, providing relevant knowledge for industry. We are mindful that whilst specialist Additive Manufacturing companies already have practical knowledge in the management of the technologies, this is often based only on their individual experiences and can be highly influenced by idiosyncrasies of their organisations and markets. Similarly, many 'conventional' manufacturing companies are beginning to consider Additive Manufacturing, although it has already been identified that potential adopters may be disenfranchised as a result of the technologies being overhyped (TSB 2012).

We connect theory to practice through the conduct of a detailed examination of fifteen case studies in Section 4, focusing on the implications arising for polymer-based industrial Additive Manufacturing systems, which are chosen given their prevalence in contemporary commercial operations (Wohlers 2019). In turn Section 5 summarises key capabilities for overcoming trade-offs, before a discussion and conclusion in Sections 6 and 7 respectively.

2. Literature review

2.1 The strategic alignment of processes with product characteristics

The economics of manufacturing have long favoured the simplicity of high-volume, low-variety production, where repetition yields economies of scale, and issues of customer choice do not feature in the production process. Variety is "the number or collection of different things of a particular class of the same general kind" (ElMaraghy et al. 2013, pp. 629), and each instance of these different 'things' is a variant. In terms of product variety, each variant is a pre-defined variation on the focal product. For example, a shoe manufacturer may offer the same style of shoe, but in defined size intervals; likewise a lightbulb manufacturer may offer varints in terms of light output or fitting style. Importantly, each variation is a defined offering by the manufacturer, and not specified by the customer.

Variety is traditionally offered by manufacturers when i) there is a market demand for it, ii) when there is an opportunity to increase profits by offering variants, and/or iii) where offering variety enables profiatable differentiation within the marketplace (Lancaster 1990). Increasing variety improves the chances of an individual customer finding the option that they require, and being able to enjoy a diversity of options over time (Halman, Hofer, and Van

Vuuren 2003). However, offering variety traditionally introduces penalties including increased manufacturing costs and complexity (Roy et al. 2010), degraded delivery speed and accuracy (Mapes, New, and Szwejczewski 1997), impaired forecasting capabilities (Wan and Sanders 2017), and diminished overall manufacturing performance (Zipkin 1995; Wan, Evers, and Dresner 2012).

The market for many manufactured goods is changing, reflecting a movement away from homogenous, mass-produced goods that attempt to satisfy customer requirements through product varients, to heterogeneous items that are produced to meet an individual customer's requirement (Piller, Moeslein, and Stotko 2004; Åhlström and Westbrook 1999; Wang et al. 2017; Turner, Merle, and Gotteland 2020; Pallant, Sands, and Karpen 2020). Many firms have identified that customers value products that are created to their own personal requirements: a recent survey results show a fifth of customers will pay upto 20% price premium for customized products, whilst almost a half (48%) will wait longer for their customized order to be fulfilled (Deloitte 2019).

Taken to the logical exteme, customization is akin to infinite variety. In theory, given an unlimited number of product variants, the exact requirement for any given customer could be pre-designed and offered through a variety strategy; however in practice this would, of course, be infeasble. Instead, product customization engages the customer as some point in the fulfillment process, so a customized product is one that is utlimately produced for the specific customer rather than satisfied by pre-determined variety, and the extent of the customization determined by the nature of customer invovement in the supply chain (Duray

2002; Lampel and Mintzberg 1996; Olhager 2003; Gosling, Hewlett, and Naim 2017; Wikner et al. 2017).

Recent work on business models finds that the ability to provide customization is often a key component of business success (Kavadias, Ladas, and Loch 2016). As with variety, in customization many of the same market-based motivators are evident in the literature, but similarly there are many potential problems including constraints on accuracy of information, heightened production costs, and extended production lead-times (Salvador and Forza 2004). Offering variety and/or customization to customers may be an effective marketing strategy to attract customers but it must be aligned to the capabilities of the manufacturer (Berry and Cooper 1999), and be deployed strategically to avoid unnecessarily draining manufacturing resources (Spring and Dalrymple 2000). Whilst variety may be desirable to the customer, for the manufacturer it can be problematic (Pil and Holweg 2004) and often attempts will be made to constrain the number of variants offered to lessen the effect on operations (Tenhiälä and Ketokivi 2012; Fisher, Ramdas, and Ulrich 1999). The negative impacts that arise for operations performance can be identified as a ‘trade-off’ arising from the offer of variety in production (Salvador, Forza, and Rungtusanatham 2002).

Research on trade-offs in production was pioneered by Skinner (1969; 1974), who described them as an inevitable consequence of the limitations of production systems, where the improvement of one competitive capability will negatively affect another. The product-process matrix conceived by Hayes & Wheelwright (1979) draws upon this concept of conflicting capabilities in its provision of a management tool focused on process selection in manufacturing. Whilst there is some debate over the validity of this work to modern manufacturing when empirically evaluated (Safizadeh and Ritzman 1996; Helkiö and Tenhiälä 2013; Ahmad and Schroeder 2002), it remains a fundamental principle of manufacturing that reaffirms variety to have major implications on manufacturing.

In essence the product-process matrix defines volume and variety combinations for which four given process types (Job, Batch, Line, Continuous) are best suited: from the job process producing short (one-off) runs of high variety products with many stops for changeovers, through to the continuous process that almost never stops and produces very high volumes of a single, standardized product. Each of these processes has its unique strengths and weaknesses summarized in Table 1[1]. However, common to each is the interplay between the competitive objectives of flexibility and cost. Processes that focus on being able to readily change between different products to offer variety and customization require flexibility; those which can avoid changes and produce high volumes can focus on production efficiencies to reduce costs. In this paper we term this trade-off the 'flexibility-cost dichotomy'.

The existence of the flexibility-cost dichotomy serves to highlight the disconnect between theory and practice in manufacturing. Theoretically, flexible manufacturing systems incur little penalty as they move from one state to another (Upton 1994), meaning that the system can switch between a range of products, and this can be done at different levels of output. If this were achieved, then companies would not need be bound by the constraints of process choice as prescribed by the product-process matrix – yet penalties do occur (Chryssolouris

[1] Some recent interpretations of the product-process matrix include 'Project' as a fifth process type, which is effectively the same as the job process, but where manufacturing is undertaken at the location of demand. We do not consider this process type to remain consistent with the original product-process matrix definition.

2006), and in practice firms do configure the processes within their manufacturing systems in terms of volume and variety requirements. Flexibility is poorly understood and difficult to achieve (Jain et al. 2013), and whilst new technologies can help to overcome some trade-offs (Ahmad and Schroeder 2002), they are unlikely to overcome them all (Sarmiento, Sarkis, and Byrne 2010). Indeed, whilst Additive Manufacturing is often heralded as being 'flexible', the term is typically used with little precision and the complexities of measuring and achieving flexibility underestimated (Eyers et al, 2018).

Characteristic	Job	Batch	Line	Continuous
Equipment and physical layout characteristics				
Typical size of facility	Usually small	Moderate	Often large	Large
Scale economies	Some, firm level	Varies	Some, plant level	Large, plant level
Process flow	A few dominant flow patterns	One or two single dominant patterns	A rigid flow pattern	Clear and inflexible
Type of equipment	Mostly general purpose, some specialization	Varies	Specialized, low and high technology	Specialized, high technology
Additions to capacity	Incremental over wide range	Varies	Incremental, but requires rebalancing	Some incremental, mostly in chunks
Bottlenecks	Shifting frequently	Shifting often, but predictably	Generally known and stationary	Known and stationary
Speed of process	Slow	Moderate	Fast	Very fast
Set ups	Frequent	Some, not complex	Few and costly	Rare and very expensive
Run lengths	Short	Moderate	Long	Very long
Process changes required by new products	Often incremental	Often incremental	Incremental and radical	Often radical
Rate of change in process technology	Slow	Moderate	Moderate to high	Moderate to high
Direct labour and workforce characteristics				
Labour content (value added)	Very high	Varies	Low	Very low
Job content (scope)	Large	Moderate	Small	Varies
Worker skill level	High	Mixed	Low	Varies
Worker training requirements	High	Moderate	Low	Varies

Table 1. Selected traditional characteristics of different process types (adapted from Hayes & Wheelwright 1984)

2.2 Volume and variety for Additive Manufacturing

Additive Manufacturing enables the creation of individual parts directly from a 3D computer model through the successive addition of layers of material, without many of the constraints inherent in 'conventional' manufacturing technologies. Low-cost *domestic* machines, often termed '3D printers', produce parts of a reasonable quality, but lack the performance, reliability, repeatability, and more sophisticated capabilities observed in *industrial* machines. The Industrial Additive Manufacturing technologies that we focus on in this study are well-established in the development of new products, either in the production of prototypes for evaluation, termed Rapid Prototyping, in the production of tooling to support conventional manufacturing processes, also known as Rapid Tooling, or in the direct production of end-user parts, namely Rapid Manufacturing. For this latter application, Holmström et al. (2010) identify eight major benefits of Additive Manufacturing:

- Elimination of tooling reduces ramp-up time and expense
- Feasible and economical small batch production
- Designs may be quickly changed
- Optimization of product designs for functionality benefits
- Economical single-unit production for custom products
- Waste reduction opportunities
- Simplified supply chains with reductions in both lead-times and inventories
- Opportunities for customization of designs.

Whilst enthusiasm for Additive Manufacturing technologies to exceed the capabilities of their 'conventional' counterparts permeates much of the literature, linkage to manufacturing concepts such as the product-process matrix is scant. For example, an early study by Lee and Lau (1999) posited that an agile production network in which Additive Manufacturing technologies were employed could theoretically accommodate all potential combinations of volume and variety. Later work by Tuck et al. (2008) suggested that the absence of all labour and a high degree of automation in Additive Manufacturing could support all volume levels, whilst still achieving a high degree of variety. Neither study links to the product-process theory, and both pose these capabilities as conceptual propositions, rather than through empirical research. By extension, whilst Helkiö and Tenhiälä (2013) do explicitly suggest Additive Manufacturing might enable a 'deviation from the diagonal' in the product-process matrix as a result of the machine's ability to produce a wide range of complex parts, theirs is a passing call for future research without empirical support to explain either how or why this would be achieved. More recently Holweg et al. (2018, pp.185) have identified "Additive Manufacturing can produce variety at (virtually) zero marginal cost", which they suggest can expand the feasible space in the product-process matrix to support higher degrees of variety over higher volume output. Whilst conceptually attractive, again there is no empirical evaluation of this proposition, nor are the characteristics of the various process types (previously outlined in Table 1) explored.

Though there has been little empirical research linking Additive Manufacturing with the product-process matrix, some general application examples can help to explain some of the potential opportunities and implications. For example, it is identified that existing literature has focused on the economics of Additive Manufacturing at a range of different volumes, though there are notable inconsistencies between the studies and in many cases very little empirical support for the claims made. A widely-cited article on the potential for 3D printing identified plastic parts are competitive with conventional production techniques at volumes of 1,000 units, and expected this to increase as technologies matured (Economist 2011).

There is, however, no explanation of the nature of these parts, nor the comparable manufacturing technology that would produce them. Similarly, Anderson (2013) noted the perceptions of one practitioner that the technologies could yield volumes of 2,000-3,000 units annually. Berman (2012) identify that 3D printing is suitable for 'small to medium' production runs, whilst Günther et al. (2014) has identified that in the production of cores for faucets, production of 50,000 pieces using Additive Manufacturing is a 'reality'. The variation in these observations suggests Additive Manufacturing may, depending on the criteria of assessment, feasibly operate at different volume outputs. Economist (2012b, pp.12) identify that there are "barely any economies of scale in Additive Manufacturing, the technology is ideally suited to low-volume production", which Merrill (2014, pp.51) extends to observe "economies of scale evaporate and mass customization becomes a reality. A batch size of one costs the same as 100 or 1,000".

In discussing the potential for Additive Manufacturing several authors have briefly noted the way in which production may be achieved in practice. Both Economist (2012a) and Günther et al. (2014) highlight that Additive Manufacturing technologies are engaged in batch processing to fulfil demand, though the potential exists to change. The opportunity to move towards a line-based production could be made possible by increasing the throughput of the machines and reconfiguring layouts (Economist (2012a). Going further, in proposing additional automation in the process equipment, Günther et al. (2014) envisage the opportunity to achieve continuous processing using specialised Additive Manufacturing technologies.

2.3. Extending the product-process matrix to accommodate customization in Additive Manufacturing

When proposed, the product-process matrix was characterized by two dimensions: *product structure,* in term of volume and standardization, and *process structure,* in terms of organization and flow (Hayes and Wheelwright 1979). Over time this work has been reinterpreted by many authors to separate the two product structure options, against which the process structures are positioned more clearly. Volume is typically plotted on the vertical axis, while standardization has replaced variety and is located on the horizontal, and individual process types are plotted against the matrix. This revised approach to the three attributes of the product-process matrix is now frequently evidenced in both contemporary teaching (e.g. Slack and Brandon-Jones 2018) and research (e.g. Helkiö and Tenhiälä 2013).

Volume of production is relatively easy to identify in a production environment, either in advance of production by forecasting or evaluating the order book, or on completion of production by using works data. Adjustments may need to be made for scrap or rework, but typically obtaining details of the number of units produced is quite straightforward. The variety observed in a production environment is a comparatively difficult value to evaluate. In a detailed review of variety measurement, Stäblein, Holweg, and Miemczyk (2011) highlight firms do not simply produce all possible variants of a product. For example, they identify that in practice manufacturers may limit the offering of variety according to market requirements, or enforce limitations on some combinations of variety offered. By extension, firms need to recognize their own limitations in production and, in offering variety, they need to ensure that they have the capabilities to deliver. Considering Ashby's Law of Requisite Variety (Ashby 1956), product variety affirms that a production system must have capability to produce at least as many product variants as offered to the customer. As a result of manufacturers actively constraining variety offered, simply multiplying the number of possible variant options will not identify an accurate value for the variety being presented.

Whilst variety through permutations and combinations of options can be complex, the challenge facing today's manufacturers is the requirement to move beyond variety, and into the customization of products and provision of engineered solutions (Willner, Gosling, and Schönsleben 2016). For Additive Manufacturing this is particularly pertinent, since the ability to produce individually customized products is often heralded as one of the core advantages of the technologies (Manyika et al. 2013; Holmström et al. 2010). Unlike variety achieved through a catalogue of options or a modularity of assemblies, customization in Additive Manufacturing allows customers to individually shape their products to meet their own requirements; in medical examples this allows bespoke products that perfectly suit an individual patient (Bibb et al. 2009). Products can be further customized in terms of the mechanical properties of the materials, allowing various parts of the same product to function differently under mechanical load, or to have different aesthetic characteristics (Wohlers 2019). Attempting to count customization possibilities using the same techniques employed in variety assessment is rather futile, and a different approach to customization evaluation is needed.

Unlike variety, customization necessitates production in response to an individual customer's desires (Pine II and Gilmore 1991), and the degree of customization achieved is determined by which stage of production or distribution the customer becomes involved (Lampel and Mintzberg 1996). Several different strategies have been suggested based on the notion of a

'Customer Order Decoupling Point' (Hoekstra and Romme 1992), ranging from fully standardised 'Make to Stock' production through to engaging the customer in product design using 'Engineer to Order' (ETO) approaches (Yang and Burns 2003; Olhager 2003; Rudberg and Wikner 2004). ETO situations are based on new or adapted designs to be created for individual customer orders, typically engaging closely with the customer in the adaptation of existing designs (Gosling and Naim 2009). A body of knowledge has emerged to guide the engineering of complex customised products in areas such as the co-ordination of design and production, design automation, and supply chain management (Willner, Gosling, and Schönsleben 2016; Mello et al. 2017; Gosling, Naim, and Towill 2013).

There are clear overlaps between the movement towards Additive Manufacturing enabled customised products, and the insights from the ETO body of knowledge. Hence, in this study we utilize ETO concepts to help us understand the extent of customization in Additive Manufacturing, and to enrich the product-process matrix. To describe the activities undertaken Gosling, Hewlett, and Naim (2017), building on the Philosophy of Engineering (Addis 1990; Bulleit et al. 2014) developed a taxonomy incorporating design principles, offering three distinct categories of ETO, each of which has three subclasses of activity as given in Figure 1. These nine decoupling points provide clear definitions by which customization in Additive Manufacturing can be analysed, which in this study we extend for presentation in the context of the product-process matrix.

- The first category is 'research', and reflects that at the highest levels of ETO, fundamental investigation may need to be performed on receipt of a customer order before product design or consideration of production can occur.

- The second category is ‘codes and standards’, which in a manufacturing context effectively refers to the creation or adoption of manufacturing rules and standards, as well as the design of wholly new products. Products in this second category do not need fundamental research, but they are new and so do need careful consideration of how they will be made, and what their design will be.

- The third category is ‘existing designs’, for which the product design is known to some degree, and the issues of the other two categories resolved. In this category an outline design for the product may exist, but will need significant adaptation and customization for individual customers. Alternatively, a finalized design may exist, for which most components are complete, but fairly minor modifications are still performed for the customer. The final possibility is that the design is complete, and no further changes are made before production.

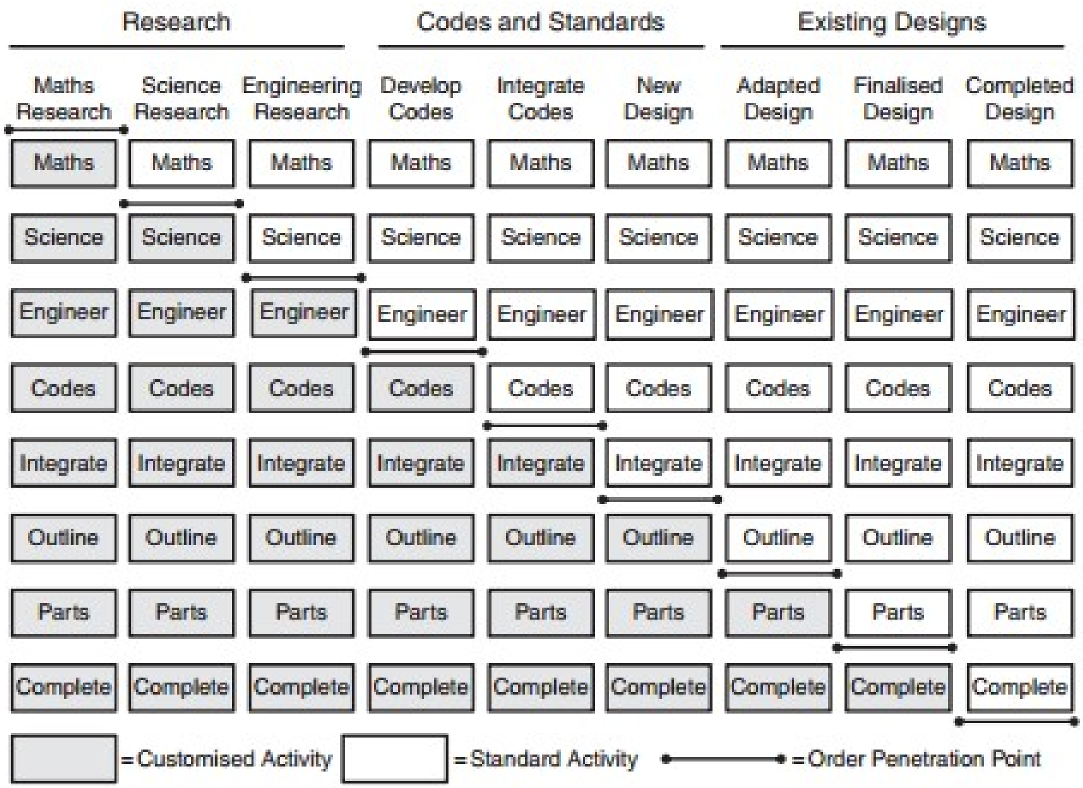

Figure 1: Engineer-To-Order types (Gosling et al. 2017)

2.4 Literature summary

This section has provided an up-to-date appraisal concerning the implications of product characteristics on some strategic choices in manufacturing. A detailed discussion explained the nature of variety and customization from the product perspective, and linkage was made to the classic product-process matrix (Hayes and Wheelwright, 1979). It was shown that whilst the technologies of Additive Manufacturing are theoretically well-suited to support both variety and customization in product manufacture, there has been scant consideration of how fundamental principles of manufacturing operations management, as typified by the product-process matrix, can be utilized. In closing the section, we highlight how supply chain research in terms of decoupling points and the related fulfilment activities may serve to integrate

Additive Manufacturing with the product-process matrix for the purposes of managing variety and customization in product manufacture.

3. Research Method

Whilst there is much enthusiasm in literature and popular press concerning the capabilities of Additive Manufacturing machines, in practice fulfilment of demand is not achieved by the machine alone. In this work we adopt the manufacturing systems approach to Additive Manufacturing defined by Eyers and Potter (2017), which recognizes the main transformation process has four components: Design, Pre-processing, Manufacturing, and Post-Processing, with system control managing the resource flows within these (Figure 2). Design concerns all aspects of design, both for new products and those which are customized. Pre-processing includes activities such as configuring the build layout or planning production, Manufacturing concerns physical part fabrication by an Additive Manufacturing machine, while Post-Processing includes cleaning the product, quality assessment or assembly of the final product. By adopting a systems approach, we therefore build a more complete understanding of how manufacturing is achieved than focusing on a single machine resource alone, and use the different system components to guide the case analysis presented later in the paper.

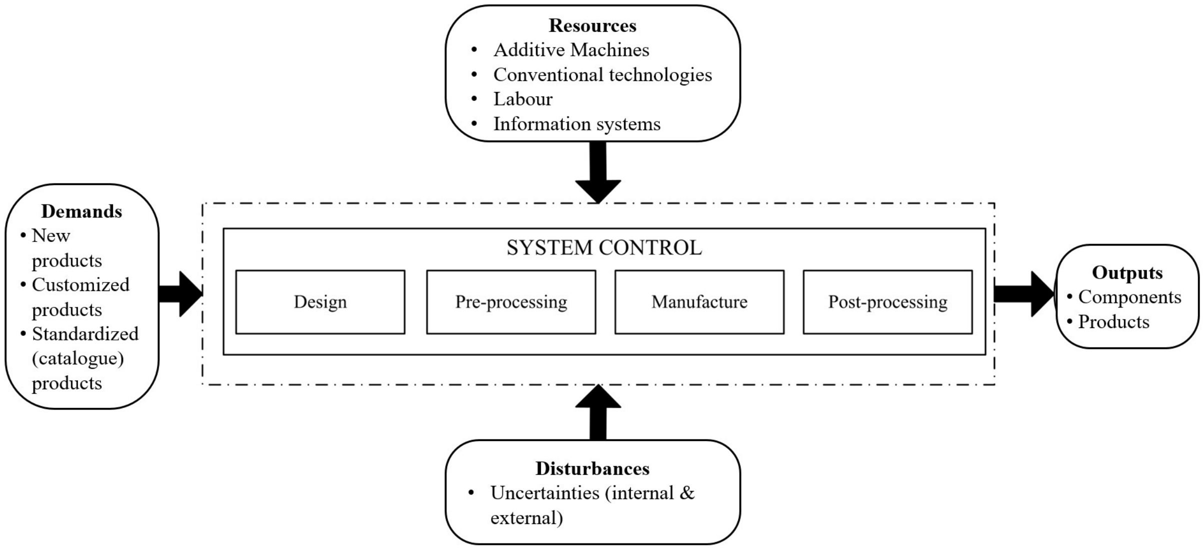

Figure 2. Concept of an Industrial Additive Manufacturing System (Eyers and Potter 2017)

Case research is appropriate for this study as although there is a general theory for the product-process matrix, existing literature does not support the derivation of *a prioiri* theoretical hypotheses, but through industrial empirical data theoretical insights can be achieved (Ketokivi and Choi 2014). We studied the operations of five industrial Additive Manufacturing companies who produce whole products or component parts on a commercial basis, using a combination of interviews and process observations to understand how production occurred in polymer-based manufacturing. The nature of the product-process matrix is that individual evaluations are made for each focal product, and so the unit of analysis for each case study is determined by the product manufactured. Following the guidance of Stuart et al. (2002) we sampled the data collected as the research progressed, using diverse cases to promote internal validity in the research.

The works of Hayes and Wheelwright (1974, 1979) on the nature of the product-process matrix provided a useful structure for the analysis of data. For each case volume, in terms of annualised production values, was sourced from the manufacturer. To understand variety/customization we utilized the general descriptors provided by the ETO typology of Gosling et al. (2017) as described in Section 3. We looked at each case in detail to understand which ETO category it was located within, together with the appropriate subclass. To understand the nature of the various production types, namely job, batch, line, and continuous, we employed clustering and pattern-matching to identify commonality and disjunction between the case examples.

4. Results

The fifteen case studies were examined in detail and classified in terms of their volume and variety/customization characteristics (Table 2). Using these results, a mapping onto the product-process matrix based on the original characteristics of Hayes and Wheelwright (1984) was made, yielding four distinct clusters. In this section we explore the nature of these clusters, highlighting the alignment and disjunction with some of the most pertinent traditional characteristics of the product-process matrix. Table 3 outlines the characteristics of the four clusters, to provide a comparison with the generic descriptions previously provided in Table 1.

Case No.	Company	Product Description	Volume (annual)	ETO type from Figure 1	
				ETO Category	ETO Subclass
1	A	In-The-Ear (ITE) Hearing Aid customized to fit individual ears.	10,000's	Existing Design	Adapted Design
2	B	Replica timbers used in the creation of a model medieval ship	700	Research	Engineering Research
3	B	Scale models of ancient stone monuments for museum exhibition.	4	Research	Engineering Research
4	B	Architectural scale models produced to visualize potential designs for new buildings.	20	Codes	New Design
5	B	Inserts used to create tools for hydroforming of exhaust systems	1	Codes	New Design
6	B	Customized inspection fixture that perfectly fits the shape of a prototype toothbrush product	1	Codes	New Design
7	B	Functional prototypes of a tool that would be used in the manufacture of car exhaust pipes	3	Codes	New Design
8	C	Surgical guides used in surgical planning to represent individual patient anatomies.	10,000's	Existing Design	Adapted Design
9	C	Lampshade with design customized by the customer	100's	Existing Design	Finalized Design
10	C	Standardized lampshade with complex geometric design	100's- 1000's	Existing Design	Completed Design
11	C	Customized fixtures for locating components in manufacturing assembly operations	100's- 1000's	Existing Design	Adapted Design
12	D	Designer furniture for exhibition in a museum	1	Research	Engineering Research
13	D	Model of headphones for marketing purposes	9	Codes	New Design
14	D	Automotive component	3	Codes	New Design
15	E	Plastic figurines for consumer collectors	100's- 1000's	Existing Design	Adapted Design

Table 2: Volume and Variety/Customization evaluation for focal cases

Cluster A: Job-based processes for low volume production of new products (Cases 2, 3, 4, 5, 6, 7, 12, 13, 14)

This cluster represents the traditional application of Additive Manufacturing technologies to produce wholly new products with a strong alignment to the low-volume, high-variety job-based manufacturing defined by Hayes and Wheelwright (1979). Producing new products necessitates many decisions about how parts should be produced, and whether designs need to be modified to reflect constraints in manufacturing. Where products are suitably novel to the manufacturer, some prototyping may be needed to understand the best way to produce parts, and designs adjusted accordingly. These cases demonstrate a close linkage between customer and manufacturer in the development of designs, and in the production of the required products.

Three cases (2, 3, 12) necessitated fundamental engineering research to evaluate the capability of the machines and material to produce products meeting the necessary specification. For example, in the model ship case (2), this required the manufacturer to conduct research into material characteristics, as well as trialling of parts to ensure very small details of the product were adequately reproduced using Additive Manufacturing. Sample parts were made, and several meetings with the customer were necessary to achieve acceptance. By comparison, whilst the other six cases identified in this cluster (4-7, 13-14) were identified as new products such fundamental research was not needed. The manufacturer had previous experience of making similar products, and therefore could apply known process parameters in their manufacture. In doing so, manufacturers draw on a relatively skilled workforce, which is consistent with traditional job-based operations:

"[In terms of new products] design work is skilled… I'd say that any of [postprocessing] is semi-skilled… but hand finishing is different because if you sand in anywhichway direction it's going to be a rubbish part, so you gotta know [what to do for the given product]. It takes about six months to get a new person up-to-scratch…"

[Company D]

Traditionally job production requires flexibility in the resources of the manufacturing system, and this is evidenced for Additive Manufacturing. Case examples in this cluster demonstrated that general-purpose resources were used to produce products in short runs. For example, in the Cases 2, 3, 4 & 7 the same Additive Manufacturing machine was used to make the products, the same post-processing equipment to finish the parts, and the same labour to undertake the different tasks. The need for frequent setups is also characteristic of job-based processes, and for Additive Manufacturing these may be observed in the need for product-specific configuration of the machines. Examples of such configuration include parameter setting for specific accuracy requirements (e.g. Cases 2 and 4), or in the setting up of the machine for specific materials (e.g. Case 5).

Although in this approach Additive Manufacturing offers flexibility to produce a range of different products, as with conventional technologies there is an associated cost arising from this. Consistent with Table 1, the cases demonstrated production as being slow, discontinuous, with multi-week lead-times often required as a result of much human effort needed in design, pre-processing and post-processing. For example, Case 2 involved 15 people in the design phase and, while the actual production lead time was 2 weeks, the average lead time for a batch of parts was over 2 months.

Characteristic	Cluster A	Cluster B	Cluster C	Cluster D
Equipment and physical layout characteristics				
Typical size of facility	Varies between cases	Moderate – multiple Additive Manufacturing machines	Moderate – multiple Additive Manufacturing machines	Large scale, whole facility
Scale economies	Some, where multiple jobs can be combined	Some, where multiple jobs can be combined	Some, where multiple jobs can be combined	Specialization of both staff and equipment
Process flow	Activity sequencing evident, but lacking flow	Well defined	Well defined	Rigid, well defined flow with known process times
Type of equipment	General purpose software and machines	General purpose software and machines	General purpose software and machines	High-tech software. General machines dedicated to focal products
Additions to capacity	Inflexible and costly, long term investment	Inflexible and costly, long term investment	Inflexible and costly, long term investment	Rather inflexible; capacity increased over extended periods
Bottlenecks	Particularly in design and preparation	Some, largely predictable	Some, largely predictable	Generally known and planned for
Speed of process	Relatively slow, in design and pre-processing	Moderate, compromised by shared resources	Moderate, compromised by shared resources	Generally fast
Set ups	Individual setups considered for all products	Setups typically similar limiting effect of changeover	Setups typically similar limiting effect of changeover	Very few
Run lengths	Very short	Moderate	Moderate	Very long

Process changes required by new products	Incremental, slow	Incremental, slow	Incremental, slow	Major investment in setting up new processes
Rate of change in process technology	Slow	Moderate, incremental and based on experience	Moderate, incremental and based on experience	Moderate. Technologies adopted once proven in other applications
Direct labour and workforce characteristics				
Labour content (value added)	Very high in design and post-processing activities	High for post-processing. Some in design and pre-processing.	High for post-processing. Some in design and pre-processing.	Relatively little except for post-processing which remains manual
Job content (scope)	Large range of job content	Moderate, but largely defined	Moderate, but largely defined	Limited. Some evidence of multi-skilling to improve flow
Worker skill level	Generally high, particularly in design.	Moderate. Many activities repetitive	Moderate. Many activities repetitive	Moderate, any jobs still require skills
Worker training requirements	High, particularly in design	High, particularly in design	High, particularly in design	Moderate, often product-specific

Table 3: Characteristics of the four identified clusters of Industrial Additive Manufacturing Systems

Cluster B: Batch-based processes for customized production (Cases 9, 11, 15)

Traditionally batch processing leads to the production of multiple identical products, and is normally employed where the repetition in production can lead to scale economies compared to job processes, but where demand is not adequate to set up a line process. In this study three cases demonstrated characteristics typical of batch manufacture, whereby general-purpose equipment was used in the production of multiple parts, though notably these parts are not identical – they are individually customized to the requirements of the customer. In Case 9 lamps are produced with customer-chosen text embedded into an otherwise standard lampshade design. This is an example of an Adapted Design, where the core product design and rules for manufacturing exist, but where some customization can be made by the customer. In Case 11 customized assembly fixtures are produced, with the geometry of the fixture surface being customized to match the product it is intended to hold. Case 15 concerns the production of plastic figurines for model collectors and hobbyists, with some geometric attributes of models customizable by the consumer. In all three cases multiple products are produced during the same production build.

“[As part of a build] we’ve got a soldier which is that tiny, there’s 50 of them, and each one is a different soldier. One has a gun, one has a different face, one has a different cap, one has a different shoe…and we have to sort them and send them individually…. But that’s the beauty of 3D printing: *manufacturing* [the printing activity] isn’t complex.”

[Company E]

Unlike the new products shown in Cluster A, these customized products have the advantage of being produced in a repetitive manner, negating the need for product development activities, prototyping, and much of the decision making. Importantly, the customization in these cases is wholly geometric, bounded by well-defined parameters, and achieved entirely by the Additive Manufacturing machine without significantly affecting other aspects of the manufacturing system. This promotes some standardization in the processes, though whilst batch processes produce higher volumes than job counterparts, general-purpose resources are still usually employed. The nature of batch processing has fewer specific setups than job processing, and run lengths are longer, with some efforts to reduce labour requirements through standardization of activities or substitution through software tools. For Company E, the well-defined nature of production included using a web-based job tracking system to update the customer on the state of their order.

"We basically upload [the configured build of multiple products], then it prints for however many hours…once the printing is finished it goes into a freezer for five minutes, then it goes into an oven for 45 minutes…then it goes into an oil bath for 20-25 minutes, then it goes into a soap bath for 20 minutes… then it goes into the dehydrator for an hour, then we are ready to QA [quality assurance]… and then packaging it for all of the parts on the tray, once that's done you put all of those parts in their box, and once that's done you print the [shipping] labels."

[Company E]

One of the manufacturing companies (C) produced hundreds of individually customized parts in batches, and so opted to develop software solutions to reduce labour requirements in the design and pre-processing stages of production. For example, in Case 9 the customer can tailor the design of the lampshade through a website and the file is automatically converted into the file used by the production machine. Likewise, whilst post-processing techniques remain labour-intensive, its repetitive nature allows for refinement and, as a result, skill reduction.

Cluster C: Batch-based process for standard products (Case 10)

This cluster highlights an interesting example of fully standardised (catalogue) products. This case does not take advantage of the customization capabilities of Additive Manufacturing machines and is therefore located at the base of the y-axis. As the production volume does not warrant the investment needed to set up a dedicated line process these standardized parts are produced in the same manner as their customized counterparts; often, the customized (case 9) and standardized (case 10) products will be produced simultaneously in the same production build. In this case there is no variety or customization, but insufficient volume to justify a line process, and therefore this case deviates from the diagonal of the product-process matrix, in doing so retaining the same characteristics in Table 3 as Cluster B.

This case makes an interesting example of disjunction with the product-process matrix. In this example the flexibility capabilities of Additive Manufacturing machines to offer customization are not employed: for conventional manufacturing this would traditionally be suboptimal with the process having excess flexibility and therefore an associated cost. However, this case shows that for Additive Manufacturing, a lack of customization makes no difference to the production machines, with the manufacture and post-processing of the lampshade taking the same time and materials to achieve as a comparable custom item.

Instead, this case shows how the general-purpose nature of the Additive Manufacturing machines, combined with policies to minimise setups and a high degree of process standardization enable firms to promote economic production. In this example fully standardized (catalogue) lampshades are typically manufactured either in expectation of a future customer order (on a make-to-stock basis), or may arise as a result of a customer order (on a make-to-order basis). In both production strategies the intention is to exploit scale economies, helping improve the competitiveness of the offering.

"[For Make-to-Order] we go for long leadtimes due to the economic pressure in this market…we look for idle time on the machines [to promote machine capacity utilization]"

[Company C]

Cluster D: Line-based processes for high customization (Cases 1 and 8)

Conventional manufacturing normally employs line production where sufficient volumes for the same product merit investment in dedicated resources. In this study Cases 1 and 8 are both evident as deviating from the normal alignment with the product-process matrix. Both are examples of medical applications, for which the nature of customization is very high, with each item made specifically to fit the individual patient requirements. This includes customized geometries and optional attributes for functionality and performance. Both examples also represent the largest production volumes achieved by the manufacturers, producing tens of thousands of each annually. They are commercially very successful and disrupt conventional approaches to production: for ITE hearing aids (Case 1) Additive Manufacturing has completely replaced traditional approaches throughout the audiology industry.

Unlike the cases shown in Cluster A, both products are classed as Adapted Designs. This means that fundamental research activities are not required for the creation of an individual part, and all the codes and manufacturing rules are already well-established. Instead, there are geometric customizations to make the products fit the patient, and it is important that every product fits perfectly. For Case 1, given that no two external ears (even of the same patient) are the same shape, then geometrically this is a highly customized product. Within this product there are some standardized attributes, such as the defined cavities within the ITE shell in which electronic components sit. These are inherited characteristics of the adapted design. These will be the same shape in all devices, but their precise location within the device may vary slightly.

Consistent with conventional manufacturing, the focal manufacturers have dedicated specific machines to the production of the products, employed product-specific software to automate tasks in design and pre-processing, and trained workers in optimal pre- and post-processing activities. Consistent with the generic characteristics in Table 1, production facilities were physically large, using design and pre-processing software that were specialized for this application. Setups are infrequent and run lengths long, with efforts made to reduce labour requirements in the activities undertaken. Flow was rigid and well-established, and the speed of production is faster as a result of automation and labour specialisation. Where bottlenecks existed in the flow of parts these were known to the organizations. In Case 1, there was evidence of resources being reallocated to overcome these. By comparison to the other cases, labour content in the production of these processes was reduced as a result of investment in software configurators for design, and defined approaches to pre-processing and machine setup. Although labour is not eliminated from the manufacturing system it is reduced through automation, and the skillset required is focused.

“This is a change compared to a couple of years ago, and what we see is that mostly if you get an application that produces volumes then you will setup dedicated machines and production lines and that of course changes the whole game, moving into a more industrial, conventional approach. You organize it, but are also getting quality from the machines – repeatability, things like that, so getting a better grip on technology.”

[Company C]

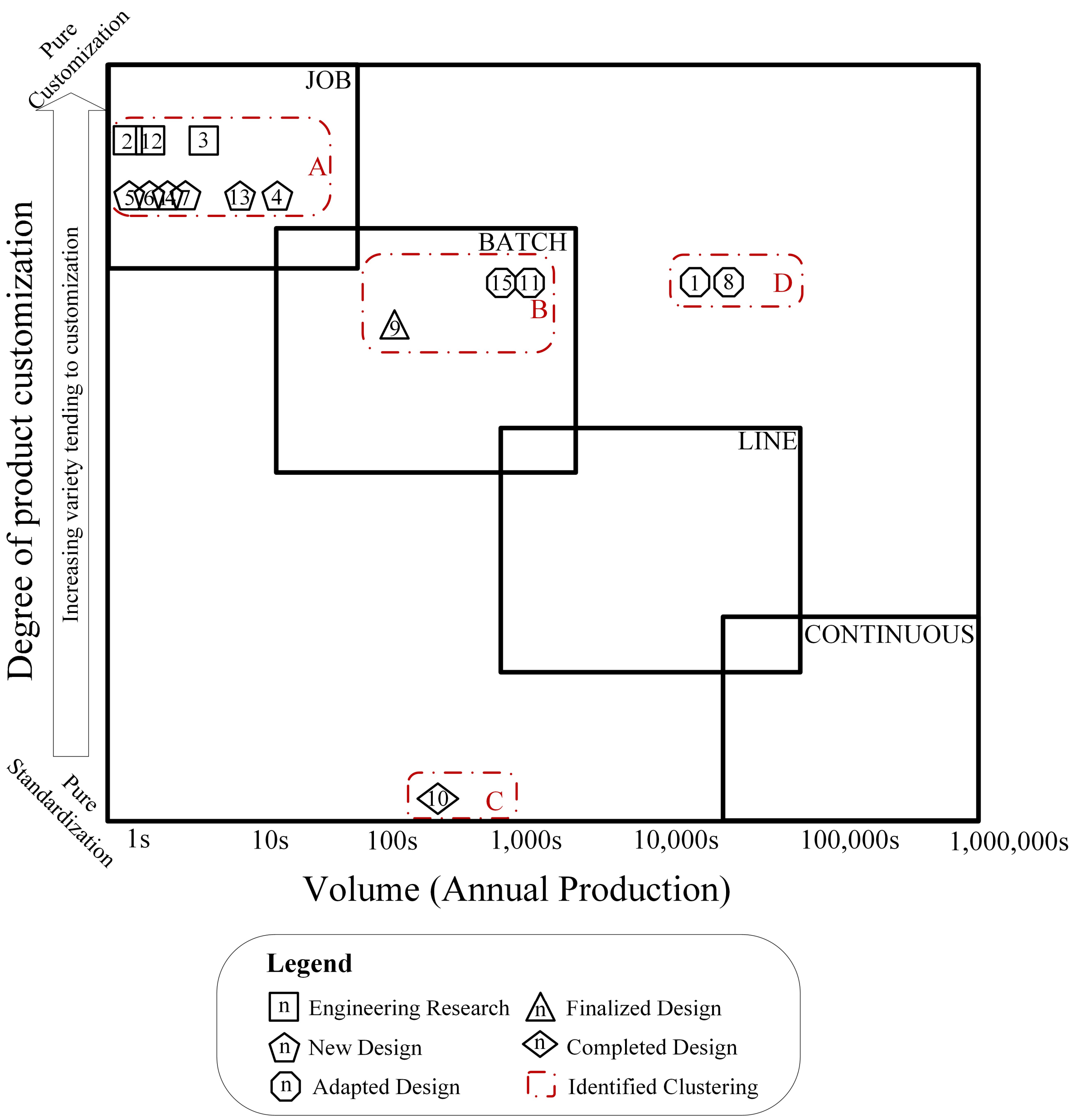

Figure 3. Product-process matrix for fifteen AM case studies

5. Overcoming the flexibility-cost dichotomy through Additive Manufacturing

In figure 3 the product-process matrix is presented, overlaid with the fifteen cases. This visually shows that in commercial practice, Additive Manufacturing can be employed to produce a wide range of volume and variety/customization options, and for twelve of the fifteen cases a good alignment to the traditional 'diagonal' exists for job and batch processes. Three examples do not (Cases 1, 8, and 10), yet they are commercially successful and this section reviews these to identify how to overcome the flexibility-cost dichotomy in terms of the four components of an Industrial Additive Manufacturing System.

System Component 1: Design. The new product development process is notoriously difficult, and as shown by Gosling et al. (2017), engages manufacturers in a wide range of activities before production can commence. In cluster A, where all products rely on either Research or Codes/Standards there is much investigation, human effort, and prototyping in the development of a design for manufacture. As a result, the flexible capabilities of the Additive Manufacturing machine are rather negated by the more significant challenges in design, which necessitate skilled labour to effectively translate the requirements into a manufacturable design.

The elicitation of customer requirements for customized manufacturing is also notoriously difficult (Zipkin 2001), but the current study shows Additive Manufacturing to afford some useful characteristics. To overcome these penalties in time and cost, Cluster D demonstrated that flexibility to move between the design of different parts without incurring large penalties is possible. As Adapted Design customization options are well defined and typically affect the shape of the product, manufacturers can use a combination of hardware (3D scanning technologies) and product-specific software tools to both less the labour required and its overall skill level. For example, in Case 1 a hearing aid shell takes about 5 minutes to 3D scan, and 10-30 minutes to configure using specialist software ready for direct manufacture. Both activities require semi-skilled technician labour. By comparison, Case 7 took over a day to design by a skilled product engineer, and then required iterations of physical prototyping to evaluate before the design was considered ready for production. It is notable that the projected production volumes in Cluster D made it viable to invest effort in the original product design to delimit the various parameters by which the product could be modified. Bounding the potential for change in this manner offers the potential to deskill and accelerate subsequent design customizations, and builds upon the existing research concerning product configurators that employ artificial intelligence techniques in support of customization management (Trentin, Perin, and Forza 2011; Haug, Hvam, and Mortensen 2012).

System Component 2: Pre-processing. Once a 3D design model has been produced, the manufacturer needs to undertake several activities in advance of physical production, including feasibility assessments, error-checking, and work scheduling. For clusters C & D the repeatability of their production means that standard operating procedures could be developed, promoting efficiency in production. Cluster D demonstrated that geometric customization has minimal impact on pre-processing, since although the geometries of the parts are all different, each is approximately the same overall size and will be manufactured using the same machine and material configuration. Cluster C has no customization, and so pre-processing requirements are also predefined. As a result, in all cases firms were able to standardise the rules for pre-processing, and thus engage the application of software tools to automate the much of process.

System Component 3: Manufacturing. The physical production of the parts in the machine is an automated and largely unattended process. Additive Manufacturing machines are well established as manufacturing complex geometries, and the nature of the customization within these case examples was shown to have negligible impact on their operation. This capability has previously been termed ‘geometry for free’ (Hague, Campbell, and Dickens 2003), and supports the flexibility of machines to be employed in the production of many different parts (Helkiö and Tenhiälä 2013). This is consistent with Case 10, however for the higher volume production we note this is enhanced by several practices engaged in by manufacturers. The volume of production for Cases 1 and 8 meant that dedicated production machines were employed with product-specific configurations, with setups maintained constant for all parts. This also helped to maximise utilization of the machines by allowing the full utilization of the build-chamber, and reduce the potential for failed builds using well-tested machine configurations.

System Component 4: Post-processing. Despite many advances in Additive Manufacturing technology since inception, post-processing remains one of the more laborious aspects of the fulfilment process. Several activities are undertaken post-manufacturing, including cleaning, quality assessment, part collation/assembly, and packing. In general it is difficult to introduce automation for many of these operations, since different products will have different requirements for which automated solutions may lack adequate flexibility to accommodate. However, for Cluster D, post-processing of the customized parts was shown to be a standardized batch operation, since the geometric customization of each product made no difference to the way post-processing was conducted. Similarly for the standardized product in Cluster C, the lack of customization allowed for process standardization. Whilst these remained largely labour-intensive activities, the manufacturers were able to draw upon the consistency of requirement and repetitive production to dedicate labour to specific tasks, promoting speed and flow in the operation.

6. Discussion

Considering the fifteen cases of this study it is apparent that the nature of the products and their volume plays a large part in the selection of process types. For nine cases, their nature as 'new products' means that firms need to undertake activities that Gosling et al. (2017) classify within 'Research' or 'Codes and Standards' categories. This inherent need for many traditional product development activities creates significant work to create a design, and to understand the best approach to its manufacture and post-processing. These activities are essential to produce the product, but the effort is amortized over a very low production volume. Consistent with the logic of the product-process matrix, these types of products fall within the typical characteristics of a job-based process, reliant on flexibility in production resources to switch between activities with low penalty.

Where volumes increase, Cases 9, 11, and 15 highlight the ability of manufacturers to exploit some of the advantages inherent in batch production and capitalise on the reduced effort needed in product development. As these are 'existing designs' much of the inherent knowledge about how to optimally produce the product is reasonably well known, though the limited volumes constrain the viability of standardized operations for the optimal manufacture of the focal product. This enables a lessening of the skill requirement in many aspects of the fulfilment process, as operations become increasingly repetitive.

Where volumes are sufficiently large, Cases 1 and 8 demonstrate that firms can make strategic decisions to overcome the cost-flexibility dichotomy. These ‘existing designs’ of the Gosling et al. (2017) classification are produced in sufficient volume to merit investment in technology to help mitigate trade-offs in design, and focus on configuring their manufacturing systems to take advantage of resource specialization, standardized procedures, and other volume-related benefits in line-based production. This allows for increased standardization in operations, lessening the need for many real-time decisions that traditionally introduce uncertainty and complexity in manufacturing operations (Thonemann and Bradley 2002). For the manufacturer of Case 1, moving from batch production of hearing aids using conventional manufacturing technology to line production with Additive Manufacturing yielded improvements in throughput and flow, such that manufacturing lead-times fell from 4 days to a single day. Likewise, in the context of the medical products of Case 8, the manufacturer identified that the ability to produce customized parts in a line-based process allowed them to pursue quality, reliability, and cost performance objectives in the same way as a conventional manufacturer. As a result, these two cases evidence how a firm can competitively operate ‘off the diagonal’ of the product-process matrix, delivering highly customized products but maintaining operating efficiencies for competitive production.

The significance of case 10 should also not be overlooked in the cost-flexibility dichotomy. Here is an excellent example of where there is theoretically too much flexibility in production, with a standard product of being produced in a batch process. However, a lack of customization makes no difference to the production machines, with the manufacture and post-processing of the lampshade taking the same time and materials as a comparable customized item. Indeed, to afford high machine capacity utilization it was commonplace to simultaneously produce such standards parts alongside highly customized items, highlighting how the flexibility of the Additive Manufacturing contributes to over overcoming the cost-flexibility dichotomy.

7. Conclusion

In introducing this paper, we noted the expectation from some authors that the capabilities of Additive Manufacturing technologies would lead to a new Industrial Revolution. Specifically, our contribution has been to explore whether Additive Manufacturing could overcome the cost-flexibility dichotomy that is a traditional trade-off inherent in the product-process matrix. Using engineering philosophy, we developed an extension of the product-process matrix to accommodate both variety and customization measures, and examined fifteen commercially produced products from five manufacturers.

We observe that for many examples Additive Manufacturing was employed in a remarkably similar (and unrevolutionary) manner to their conventional manufacturing technology counterparts, and we recognize that many of the traditional characteristics defined by Hayes and Wheelwright (1984) are readily observed in these case studies (although we acknowledge that no applications for continuous production were studied).

However, our empirical investigation also demonstrated three examples that show clear deviation from the established theory. Skinner (1992) previously identified that new technology may help to abate trade-offs, and in three cases, we show how trade-offs are overcome through the application of Additive Manufacturing. In a detailed discussion we highlight the characteristics of both the products and manufacturing system configurations that facilitate this achievement.

What is evident from our research is that although the machines can produce virtually any geometric shape at no additional cost, when incorporated into a wider manufacturing system the benefits from this flexibility are often reduced. By integrating the finely granulated ETO taxonomy of Gosling et al. (2017) within the product-process matrix, it is apparent that the fundamental challenges of research, code/standards development, and original product design offer higher levels of customization, but through the cases it is shown that these impact the operations of the manufacturer. By comparison, where such preparatory activities are not required and customization entails the geometric adaptation of an existing design, the impact on the manufacturing system is relatively small. This can support higher volume production and allow firms to move towards line based production of customized products, achieving flexibility without a corresponding cost increase. Whilst our research focused on polymer, rather than metal-based Additive Manufacturing, we would expect these same challenges to hold in the elicitation of designs.

For practitioners several key characteristics from the integration of Additive Manufacturing into a manufacturing system were identified, which may offer insights into opportunities where the technology may be fully exploited and especially where the flexibility-cost dichotomy can be overcome. This allows them to competitively offer products of a wide range of customization, without incurring notable penalty in their operations.

Firstly, we note that many aspects of design remain problematic, and we find no easy solution to overcoming fundamental research or codes/standards development issues. These are inextricability linked to underlying scientific, mathematic, and engineering skills, and the ratification of professional societies and national standards bodies (Gosling et al., 2017). From the external perspective, building good links with these organizations may be advantageous both in knowledge acquisition for the company, and to influence the generation of standards. Internally, the dependence on advanced skills suggests a reliance on effective personnel recruitment and development, together with appropriate integration of production and sales/marketing functions to ensure alignment between product offerings and firm capabilities.

However, our research shows that some opportunities present where existing designs are available. For this, one of the key elements is to ensure adequate volumes to merit investment in resources, particularly in terms of software and machines. For design, investment in software configurators can move much of the work to the customer, lessening the work for the manufacturer. Related work in co-design and co-creation has already highlighted its contribution for product customization (Irani et al. 2017; Piller, Moeslein, and Stotko 2004), and the digital nature of Additive Manufacturing design files makes elicitation via a web interface relatively straightforward. This can help shift the burden of design to the customer, which offers opportunities to lessen the manufacturers costs and, in some cases, potential liabilities arising from designs. Such an approach enables greater automation of the design and pre-processing stages, reducing the labour requirements often evident when customization is required, and the creation of dedicated production lines which are configured for the manufacture of a specific product.

The second insight for practitioners is to ensure customization is anticipated in advance, and manufacturing strategies planned accordingly. For example, although the overall shape of the products in Cases 1 and 8 differ, being tailored to specific patients, their overall sizes are largely consistent and therefore activities in design, pre-processing, and post-processing can be standardized and automated, just as for the standardized Case 9. In this way the flexibility capabilities of Additive Manufacturing machines can be appropriately exploited to produce customized products, and these suitably supported by other activities within the manufacturing system.

It is pertinent to reflect on how the original characteristics of the product-process matrix, summarised in Table 1, provides a third insight for practitioners. In many of the cases we have shown much alignment with the established norms of production. For example, low volume, highly customized parts with much design requirement (e.g. Cluster A) closely align to the job process characteristics with relatively slow processes, limited flow, short runs, and a reliance on higher skill levels in labour. However, what is observed in those cases that show deviation from conventional limitations is a change in some of the expected attributes of the product-process matrix. For example, whilst line processes would normally employ specialised equipment, in Cluster D we find general-purpose Additive Manufacturing machines being employed in production. Likewise, line processes typically engage lower-skills in the workforce, yet Cluster D highlights a need for moderate (and sometimes highly) skilled employees to support production. Normally line processes remain consistent in their configuration, with change being considered 'radical', yet in Cluster D we find (albeit slow) incremental changes in to the way processes are operated an organized. Considering Cluster C to typical batch process characteristics, we note that the application of Additive Manufacturing technologies may reduce the range of different pieces of equipment used, but the relatively expensive nature of Additive Manufacturing machines may rather constrain opportunities to increase capacity.

In terms of future research, we identify several pertinent areas for fruitful study. Within the current work we highlight that three cases in this research certainly show the potential for disjunction from the established ways of strategically managing manufacturing processes, but this will not bring about a significant manufacturing revolution. Additive Manufacturing machines clearly offer unique capabilities for producing customized geometries at varying volumes, but much more research is needed to understand the constraints that hinder the development of new products. We have shown how design configurators can assist in the elicitation of customer requirements, but in the future it is likely that further developments in artificial intelligence (AI) will be able to further ease the challenge of both new and customized products (Chen et al. 2019). Whilst we acknowledge a growing body of fundamental research considering AI in some aspects of pre-processing and process monitoring for Additive Manufacturing (Wang et al. 2020), much research scope remains to consider AI for customer engagement, particularly in process selection and designing for Additive Manufacturing.

Similarly, in recognizing the value of manufacturing *systems* over individual disparate resources (Parnaby 1979; Ackoff 1997; Parnaby and Towill 2009), in this study we highlight how other system components (e.g. labour) play an important role in effective demand fulfilment. Initiatives such as Industry 4.0 and Smart Factories have highlighted the enabling role of Additive Manufacturing, but as yet there has been limited emphasis on how Additive Manufacturing systems are effectively integrated and controlled given the different demand requirements presented through the product-process matrix.

Finally, there is a significant opportunity to understand how firms may innovatively and strategically leverage Additive Manufacturing technologies. For example, emergent research has highlighted the potential for Additive Manufacturing to underpin product-service system business models, either in servitization or productization (Lahy, Wilson, and Eyers 2020; Lahy et al. 2018; Zheng et al. 2018), or in distributed production (e.g. Holmström et al. 2010; Cerdas et al. 2017; Ryan et al. 2017). These studies highlight much opportunity for Additive Manufacturing to be deployed for competitive advantage, though typically do not focus on the process-level detail examined in the product-process matrix (a notable exception being Kumar et al. (2020)). As a result, there is a general need for more research that connects these powerful concepts with operationalizable practice, and we suggest the product-process matrix remains a valuable tool with which to achieve this unified approach.

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