emerald PUBLISHING

International Journal of Operations and Prod
Manag

# Breaking the Mould: Achieving High Volume Production Output with Additive Manufacturing


| | |
|---|---|
| Journal: | *International Journal of Operations and Production Management* |
| Manuscript ID | IJOPM-05-2021-0350.R2 |
| Manuscript Type: | Impact Pathways |
| Keywords: | Additive manufacturing, Economies of scale, 3D printing, COVID-19 |
| | |

# Breaking the Mould:

## *Achieving High Volume Production Output with Additive Manufacturing*


### Abstract

**Purpose:** To examine a discrepant industrial case that demonstrates how to achieve economies of scale with additive manufacturing (AM), thereby expanding the scope of AM beyond high-variety, customised production contexts.

**Design/methodology/approach:** Abductive reasoning is applied to analyse a case of using AM to compete with conventional production, winning a contract to supply 7,700,000 products. Comparing this case to existing theories and contemporary practices reveals new research directions and practical insights.

**Findings:** Economies of scale were realised through a combination of technological innovation and the adoption of operations management practices atypical of AM shops (e.g. design for volume, low-cost resource deployment, and material flow optimisation). The former improved AM process parameters in terms of time, cost, and dependability; the latter improved the entire manufacturing system, including non-AM operations/resources. This system-wide improvement has been largely overlooked in the literature, where AM is typically viewed as a disruptive technology that simplifies manufacturing processes and shortens supply chains.

**Originality/value:** It is empirically shown that an AM shop can achieve economies of scale and compete with conventional manufacturing in high-volume, standardised production contexts.


**Keywords:** Additive manufacturing, Economies of scale, 3D printing, COVID-19

**Paper type:** Impact pathways

## 1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing (3DP), overcomes conventional manufacturing constraints, such as inventory buffers and tooling requirements, through its distinctive "general purpose" manufacturing capability (Hedenstierna *et al*., 2019). It has the potential to rapidly produce an almost unlimited range of products. Yet despite these attractive characteristics, the anticipated revolutionary impact of AM on manufacturing operations and supply chains (e.g. Brennan *et al*., 2015; Frank *et al*., 2019; Ghobadian *et al*., 2020) has not occurred for most products and industries.

AM has traditionally achieved commercial success in prototyping and other high-variety, low-volume applications where its flexibility to customise output has compared favourably to conventional manufacturing approaches. There are also recent examples of high-variety, high-volume applications of AM (e.g. Eyers *et al*., 2021). However, AM has made no real insurgence into low-variety, high-volume mass manufacturing contexts, as this requires the cost efficiency to repeat that so often characterises conventional manufacturing. In this paper we explore how a combination of technological and operational innovation allowed a firm employing AM to directly compete with conventional manufacturing during the COVID-19 pandemic in a high-volume, standardised production context.

The unique flexibility and responsiveness capabilities of AM have contributed to overcoming the global shortage in personal protective equipment (PPE) during COVID-19 (Tareq *et al*., 2021). As conventional supply chains buckled in the early stages of COVID-19 (Van Hoek, 2020), hospitals turned to AM for a range of PPE requirements, and we were able to study how 3DP firms responded. One firm, Photocentric, stood out from numerous offerings of 3D-printed PPE by supplying millions of printed face shields to the National Health Service (NHS) in England. It became a key partner commissioned by the UK Government during COVID-19 together with 33 other UK manufacturers, most of which used conventional manufacturing technologies (UK Government, 2020). Exceptionally, the company demonstrated the potential of AM to achieve economies of scale, widely perceived to be a considerable shortcoming of AM (Baumers and Holweg, 2019) that has limited the scope of its application and prevented its growth for decades (Ghobadian *et al*., 2020). This discrepant case runs counter to the extant literature and most current commercial applications of AM, leading to novel insights. Unpacking Photocentric's success may therefore unlock the barriers to growth for AM more generally. Hence, this study asks:

(1) How did Photocentric achieve economies of scale in AM?

(2) What does this mean for the future of AM practice and research?

## 2. Background

As COVID-19 spread around the world in early 2020, we witnessed numerous AM technology applications that sought to address local PPE shortages. Motivated by a desire to better understand what this meant for the management of operations and supply chains, we initiated interviews with companies producing PPE via AM. Most companies were making small quantities of PPE for local hospitals and other healthcare facilities; Photocentric was different.

Photocentric quickly scaled up to enable 3DP production levels that were comparable with conventional manufacturing, but with competitive pricing to secure the government contract. A specially designed 'print farm' factory, fitted out with 45 Magna printers operating 24/7, capable of printing 50,000 components a day, was built in three weeks to supply the NHS with 7,700,000 face shields. This case perplexed us because the company appeared to be pushing the boundaries of AM and defying the logic of previous studies that had concluded the 'sweet spot' for AM was in offering variety and customisation, not high-volume standardisation. Would contemporary practice prove theory wrong?

## 3. Methodology

A discrepant case like Photocentric – that contradicts existing theory and therefore falsifies it – has great pay-off for theory development, where its sharply contrasting characteristics are particularly relevant (Voss *et al*., 2002). We explore how Photocentric succeeded and the implications for AM practice. As we start from a discrepant empirical observation, abductive reasoning is applied whereby empirical evidence is used to refine existing theory, propose new theory, and outline future research directions (Mantere and Ketokivi, 2013). The cross-sectional case analysis, using all the interviews that formed a larger study, helped to identify the uniqueness of the Photocentric case and the associated contrasting characteristics (Voss *et al*., 2002).

Evidence specific to Photocentric was collected via multiple semi-structured online interviews with the Managing Director (MD) and triangulated with secondary data from the company's published documents and other industry sources. All interviews were conducted by two interviewers and guided by interview protocols agreed by all members within the research team. The interviews were transcribed by the interviewers before detailed analysis was performed by the whole team. Data analysis was centred around identifying contrasting characteristics, with findings confirmed with the MD. Following the query of 'how', we identified two main interconnected drivers that differentiated Photocentric from other companies: (1) technological innovation, and (2) the application of operations management practices atypical for AM, as discussed next.

## 4. How did Photocentric Succeed in Providing Economies of Scale with AM?

### 4.1 Technological Innovation

AM encapsulates a multitude of different process technologies that all fabricate parts from a 3D model. The technology behind Photocentric employs 'Daylight Photo Printing' (DPP) using light from conventional Liquid Crystal Displays (LCD) to cure many liquid photopolymer resin layers to quickly form a 3D-printed part. This technological innovation enables process performance improvements in time, cost, and dependability, which would not have been possible with other similar AM technologies. Paul Holt, the firm's MD, commented on how DPP enhances the performance of the printing process in three key dimensions:

- Reduced unit processing times: *"LCDs had the benefit of being scalable. In simple terms, we could do* [large] *areas while others did* [small, individual] *dots"*. LCD screens flash an entire layer instead of a single point, which significantly reduces the print/process time, and this was a critical element that enabled Photocentric to economically compete with conventional mass-manufacturing technology (e.g. injection moulding).
- Reduced direct cost: "*Photocentric's 3D printers use LCD screens from mobiles, televisions and tablets, making them more affordable than SLA/DLP* [stereolithography apparatus/ digital light processing] *technologies, but offering the same quality*". Cost reduction enables new markets for AM where products are not restricted to the niche, high-value domains commonly perceived in the AM literature (Ghobadian *et al*., 2020).
- Increased dependability: "*The key to* [over 90% utilisation] *is the TV screen. TVs don't break. They go on and on…You don't expect to come home and your TV stops working, but you would expect a digital light projector or a laser to be out of focus or to burn out*". The risk of build failure increases with the number of build layers, which means that increases in build volume are limited because, at a certain point, the costs of build failure will outweigh the gains of build volume (Baumers and Holweg, 2019). DPP enhances the dependability of printing operations, addressing the problem of failure costs that have inhibited AM's ability to scale up in terms of machine utilisation.

These technology-enabled operational advantages allowed Photocentric to quickly respond to critical demand, not only via commonly-known design flexibility (without tooling constraints) but also via the possibility of instant availability and the rapid scaling-up of volume, in comparison to conventional manufacturing. The MD explained: "*The obvious answer was to use* [conventional] *injection moulding and make them* [face shields] *in the UK. But PPE wasn't being made in the UK and there weren't any tools…The answer had to be printing. The way to do it of course was to make more of the* [Magna] *printers...Almost exactly three months ago, we designed the first one* [face shield]. *It shows how quickly you can start your business…We are on* [design] *iteration 25. That's the joy of 3D printing. You just iterate to make something better, if you can make it perform better, have less material or print better, you can do it. If you can find little things, you just change all the time without cost*". The first box of face shields was sent to the NHS within a week from scratch, including the time required for product design, consultation, and optimisation (product and process).

**4.2. Adopting Operations Management Practices Atypical to AM**

While DPP provided Photocentric with a unique technical edge, technological innovation does not automatically lead to success. In many 3DP firms there is typically limited emphasis on operational issues such as material flow or operational procedures that go beyond the core (AM) manufacturing process. To provide high volume at low cost, Photocentric had to radically change their AM shop design and management in terms of *volume* provision, the deployment of *resources,* and the optimisation of *material flow*. A craft shop was transformed into a manufacturing system within three weeks, including building a production line, automating post-processing, and developing production control software.

*4.2.1 Design for Volume*

AM companies producing PPE mostly operated in a distributed fashion, using widely recognised designs. For example, many organisations (e.g. 3DP bureaus) and individuals printed face shields from an open-source design in small quantities. This created significant problems, as stated by the MD: *"Everyone was using different materials assembled in multiple sites. That's not the answer"*. In theory, if there are enough individuals (e.g. a collaborative 3DP bureau) supplying an item then they eventually offset the speed/volume constraint of a technology, thereby providing an aggregated high volume. But such a practice offers no consistency in terms of quality assurance over the actual outcome, let alone over the costs for individuals. The MD stated: "*They'll* [3DP bureaus] *make you a face shield but they'll probably charge you about £15* [for one unit] *because that's a fair price for the one-off effort, the price of the resin and the amortisation of the equipment*". In other words, there are no economies of scale.

Photocentric developed their own design tailored for DPP and optimised the printing process. This enabled a significant improvement in print speed, from 20 minutes per item to 57 seconds per item, which was critical to achieving production volumes. As illustrated by the MD: "*We went back to look at the* [open-source] *design. It was obviously designed for their own FDM* [fused deposition modelling] *printers, not for LCD. The design is inextricably linked to the printing process; unless you optimise it, it just isn't worth doing as it's just too slow. We could only place four of the FDM items on a bed while we could do 210 items on ours. So, we've moved two orders of magnitude larger. We optimised the product to the process*". The strategy for Photocentric has always been to achieve high volumes at low cost, which provided them with a unique capability to design both product and process to achieve economies of scale.

*4.2.2 Low-Cost Resource Deployment*

Photocentric's competitive pricing was rooted in their in-house supply of both focal and facilitating resources. As the MD pointed out: "*We made the printers, we made the resin, and then we made the parts. That's actually the only deal you can have if you want to compete with injection moulding*". Both material costs and resources/machines that are tailored for the product become critical when cost-efficiency is a competitive criterion. For example, AM material prices were high in the past because of a high degree of material specificity to certain AM processes (mandated by the machine manufacturer). Photocentric's capability to build their own equipment and materials also allowed for the rapid scaling and tailoring of resources. The MD explained how expanding the machine size to increase output was suboptimal once the alignment with other resources (e.g. human operators) was considered: "*I went for a very large screen when I first started. The first printer that I made for mass manufacture was 98 inches in diameter and I subsequently went down to the 40-inch format. However, it was Magna's 24-inch format that was the only production-effective size. Actually, the first thing you have to tackle is how it will work with the human. Even though we'll have completely automatic processing, we won't automate removing platforms from printers because it's not cost-effective*".

In addition to optimising the *focal resource* (e.g. the Magna printer), the prompt and effective deployment of *facilitating resources* (e.g. post-processing, and production control software) was also an important element. AM machines alone do not deliver a final product or component part (Eyers *et al*., 2018), and many supporting operations/resources from conventional manufacturing remain relevant (Thürer *et al*., 2021). Photocentric clearly recognised this, as highlighted by the MD: *"We put in some automatic post-processing system* *which we developed for the face shields project. So, some washing, some conveyorised post-processing, with a custom module to flip the* [3D-printed] *parts over. And we got into a very nice regular part pattern that made a quarter of a million* [units] *a week".*

*4.2.3 Material Flow Optimisation*

To fulfil the volume of the NHS contract, Photocentric purpose-built the print farm and hired 60 new staff. This required rethinking the facility layout to improve flow. This is not a typical problem in AM operations that deal with small-scale production. As emphasised by the MD: "*The idea of mass manufacturing means you have to have a totally different look at it* [AM]. *I mean everything was different…We had to work out how to put them* [45 Magna printers] *together to go and work effectively because previously we were just doing what everyone else does, which is to take a print, have a wash station, and have a cure station".* Simultaneously, they needed to install a new planning and control system to maintain a smooth workflow across resources. The MD added: "*We developed software to control the printers. If you've got one printer, it's dead easy. You just wait until it finishes, go in, and refill it. But if you've got 45 of them, you need a control system. So, we've developed our own control software".*

In this sense, as the operation grew, Photocentric encountered some of the challenges of conventional manufacturing. The MD stated: *"The elements that we've tracked through our manufacturing system, we can see where the efficiencies and inefficiencies are… They* [printers] *all went green or red. When they go red, obviously it's time to change so we are not burning them. And then we installed a QR* [quick response] *code system to track raw materials through to finished parts so we could check and track our parts for quality reasons".* A main innovative aspect was the continuous tracking and tracing of both products/materials and resources/processes; the latter was particularly essential for maintaining a high level of dependability in a multi-printer facility.

## 5. Rethinking AM Practice and Research

AM has traditionally achieved commercial success in prototyping and other high-variety applications where its flexibility to customise output has compared favourably to conventional manufacturing approaches. Our study extends the application domain of AM further. Combining technological innovation with the adoption of operations management practices that are not commonly applied in AM shops allowed Photocentric to realise the seemingly impossible – creating economies of scale to compete with conventional manufacturing. This opens up new pathways for AM practice and research, as briefly discussed below.

The extant literature (e.g. Baumers and Holweg, 2019; Ghobadian *et al*., 2020**)** has identified three main issues that prohibit economies of scale for AM compared to conventional manufacturing: (1) the print speed is too slow for standard items to be produced in high volumes; (2) the cost of build failures prevents maximising machine capacity utilisation and throughput; and, (3) the volume/quantity advantage vanishes (or is disrupted) if a new print cycle or machine is added, as this introduces additional operational costs. Our discrepant case suggests that the first two issues can be addressed by new technologies that enable sufficient improvements in speed and dependability. Speed can be further enhanced by using multiple machines simultaneously. The risk of build failures also reduces (and consequently dependability increases) as the size of the machine reduces – a shop with many small machines is more dependable than one with fewer (but larger) ones. These aspects however appear to worsen the third issue above as they increase the number of machines. However, as exemplified by the Photocentric case, additional operational costs become less relevant once sufficient volume is produced. For example, even if materials are not produced in-house, volume still enables bulk pricing. This leads to the following research issues:

I. What other viable markets can be identified for high-volume AM?
II. How should a high-volume AM shop be configured, considering the trade-offs between speed, dependability, and operational costs?

The literature often argues that advanced manufacturing technologies such as AM will lead to a breakthrough in the performance frontier, providing a viable alternative to conventional manufacturing technologies or practices (e.g. Frank *et al*., 2019, Ghobadian *et al*., 2020). But advanced manufacturing technology is often just an enabler. How the technology is applied and managed is what constrains the disruptive power. For example, Ghobadian *et al.* (2020) argued that AM has the potential to lead Lean Manufacturing to its 'final frontier', whereas we have found that lean principles were a distinctive enabler of an effective AM mass production system at Photocentric. This qualitative empirical evidence extends recent survey literature that found a correlation between lean and Industry 4.0 implementations (Tortorella and Fettermann, 2018; Rossini *et al*., 2019). It highlights that lean and Industry 4.0 implementations may not always be separated or occur sequentially. Rather, they can occur concurrently, specifically when technology is produced in-house meaning it can be adjusted to meet operational needs. Our evidence further suggests that AM works side-by-side with conventional manufacturing; thus, the challenges and best practices of conventional manufacturing remain relevant. The MD commented on what a difference a system, including non-AM facilitating operations/processes, can make as it improves: "*When we started, we had lots of peaks and troughs, and failures in everything such as a fire in one of the conveyors from parts getting stuck … probably everything that could go wrong did! Now it's just consistent. You don't really see the change happening. We are now at an efficiency of over 90% on productivity and we have optimised processing waste and machine utilisation*". Following this discussion, two more research issues emerge:

III. How should the design of the product, production process(es), and supply chain be adapted to reflect the specific requirements of high-volume AM?

IV. What operational issues must be resolved when integrating AM and conventional manufacturing operations?

Most fundamentally, our case questions one of the main assumptions about the competitive positioning of AM – that it is only an economic solution in high-variety contexts. The empirical evidence suggests AM can achieve economies of scale if appropriate technologies and management practices are employed. This requires us to rethink the application of AM, where the advantages of the technologies can be leveraged contingent on the market requirements. Finally, other research issues of relevance to the wider application of AM include:

V. Is high volume the only way forward if AM is to enter its growth phase? Or are there alternative, divergent futures or operational pathways for one-off/low-volume AM customisers and mass AM producers?

VI. How can existing operations management theories and practices be adapted or further developed to support the growth of AM applications?

## 6. Conclusions

This paper has reported on a discrepant case of industrial practice – an AM shop that realised economies of scale and supplied millions of face shields to the NHS in the UK at the onset of the COVID 19 pandemic. This contrasts the prevailing view in the literature that the competitive advantage of AM is *variety* (the flexibility to customise) not *volume* (the cost-efficiency to repeat). The key to achieving high volume production with AM is a combination of technological and operational innovation. The latter is often overlooked for AM, where the assumption is this disruptive technology simplifies manufacturing processes and shortens supply chains. The case also highlights that the competitive advantage of the technology may well depend on whether the product and the manufacturing process are designed to leverage its strengths.

A main limitation of our study is that Photocentric is a single case creating a simple product. Future research could explore whether the results can be replicated with more complex geometries or whether this first requires further technological and/or operational innovations. Finally, as the need for PPE eased, *Photocentric* stopped supplying to the NHS and started to focus on new challenges. Around this time, we observed how PPE sourcing behaviour was creating a bullwhip effect. Future research could explore how the ability of AM to quickly scale down when compared to conventional manufacturing (and supply chains) can attenuate this dynamic phenomenon.

## References

Baumers, M. and Holweg, M. (2019), "On the economics of additive manufacturing: Experimental findings", *Journal of Operations Management*, Vol.65 No.8, pp.794-809.

Brennan, L., Ferdows, K., Godsell, J., Golini, R., Keegan, R., Kinkel, S., Srai, J. S., and Taylor, M. (2015), "Manufacturing in the world: where next?", *International Journal of Operations & Production Management*, Vol.35 No.9, pp.1253-1274.

Eyers, D. R., Potter, A. T., Gosling, J., and Naim, M. M. (2018), "The flexibility of industrial additive manufacturing systems", *International Journal of Operations & Production Management*, Vol.38 No.12, pp.2313-2343.

Eyers, D. R., Potter, A. T., Gosling, J., and Naim, M. M. (2021), "The impact of Additive Manufacturing on the product-process matrix", *Production Planning & Control*, in press.

Frank, A. G., Dalenogare, L. S., and Ayala, N. F. (2019), "Industry 4.0 technologies: Implementation patterns in manufacturing companies", *International Journal of Production Economics*, Vol.210, pp.15-26.

Ghobadian, A., Talavera, I., Bhattacharya, A., Kumar, V., Garza-Reyes, J.A., and O'Regan, N. (2020), "Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability", *International Journal of Production Economics*, Vol.219, pp.457-468.

Hedenstierna, C.P.T., Disney, S.M., Eyers, D.R., Holmström, J., Syntetos, A.A., and Wang, X. (2019), "Economies of collaboration in built-to-model operations", *Journal of Operations Management*, Vol.65 No.8, pp.753-773.

Mantere, S. and Ketokivi, M. (2013), "Reasoning in Organization Science", *Academy of Management Review*, Vol.38 No.1, pp.70-89.

Tareq, Md. S., Rahman, T., Hossain, M, and Dorrington, P. (2021), "Additive manufacturing and the COVID-19 challenges: An in-depth study", *Journal of Manufacturing Systems*, in press.

Thürer, M., Huang, Y., and Stevenson, M. (2021), "Workload control in additive manufacturing shops where post-processing is a constraint: an assessment by simulation", *International Journal of Production Research*, Vol.59, No.14, pp.4268–4286.

Tortorella, G. L. and Fettermann, D. (2018), "Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies." *International Journal of Production Research*, Vol.56 No.8, pp.2975–2987.

Rossini, M., Costa, F., Tortorella, G. L., and Portioli-Staudacher, A. (2019), "The interrelation between Industry 4.0 and lean production: An empirical study on European manufacturers", *The International Journal of Advanced Manufacturing Technology,* Vol.102 No.9–12, pp.3963–3976.

UK Government. (2020). Press release: New UK deals will bring millions more PPE items to frontline healthcare staff, 6th June 2020. Available at: https://www.gov.uk/government/news/new-uk-deals-will-bring-millions-more-ppe-items-to-frontline-healthcare-staff. Last accessed: 8th September 2021.

Van Hoek, R. (2020), "Research opportunities for a more resilient post-COVID-19 supply chain – closing the gap between research findings and industry practice", *International Journal of Operations & Production Management,* Vol.40 No.4, pp.341-355.

Voss, C., Tsikriktsis, N., and Frohlich, M. (2002), "Case research in operations management", *International Journal of Operations & Production Management*, Vol.22 No.2, pp.195-219.