

## **Title: Leveraging Digital Design and Manufacturing Processes for In-House Spare Parts Production: A Living Lab Experiment**

Hadley Brooks<sup>a</sup>, Ruben Janse van Vuuren<sup>b</sup>, Emily Miller<sup>b</sup>, Ian Sherrington<sup>a</sup>

<sup>a</sup>University of Lancashire, PR12HE, United Kingdom

[hlbrooks1@uclan.ac.uk](mailto:hlbrooks1@uclan.ac.uk), [isherrington@uclan.ac.uk](mailto:isherrington@uclan.ac.uk)

<sup>b</sup>ServiceSport (UK) Ltd, PR67BX, United Kingdom

[ruben.jansevanvuuren@servicesport.com](mailto:ruben.jansevanvuuren@servicesport.com), [emily.miller@servicesport.com](mailto:emily.miller@servicesport.com)

Corresponding author: Hadley Brooks [hlbrooks1@uclan.ac.uk](mailto:hlbrooks1@uclan.ac.uk)

### **Abstract**

This study explores the implementation of digital design and manufacturing technologies for aftermarket spare parts production in the fitness equipment restoration industry. Through a two-year action research project within a living lab setting, we assess the feasibility, profitability, and operational impact of establishing a digital manufacturing cell in a company without prior experience in this domain.

The research employs a mixed-methods approach, combining quantitative analysis of production data with qualitative case studies of specific new products. Key findings reveal significant cost savings, reduced lead times, and enhanced supply chain resilience through the adoption of additive manufacturing (AM) and CNC technologies. Within the first year, the manufacturing cell produced over 5,000 parts, with 17% addressing urgent demands, demonstrating the ability to meet variable and time-sensitive production needs. However, challenges such as the continuous need for reverse engineering skills and managing demand fluctuations were identified.

This paper advances understanding by providing a detailed, empirical framework for SME adoption of digital manufacturing technologies, addressing gaps in the literature related to practical implementation and scalability. Furthermore, the integration of intellectual property considerations and sustainability practices enriches the study's relevance. By offering actionable insights and a replicable framework, the research contributes to the economic and operational viability of SMEs transitioning to digital manufacturing, particularly those with limited resources and predominantly non-graduate workforces.

**Keywords:** Additive manufacturing, CNC technology, Reverse engineering, Sustainability, Aftermarket spare parts, Framework.

**Abbreviations:** Small & medium sized enterprises (SME), Fused Filament Fabrication (FFF), Masked Stereolithography Apparatus (MSLA), Original Equipment Manufacturer (OEM)

## **1. Introduction**

### **1.1 Digital Manufacturing of Spare Parts**

The potential of digital manufacturing, especially additive manufacturing (AM), to revolutionise the spare parts industry is a recurring theme in contemporary research [1-16]. The flexibility, scalability, and capacity of AM to produce complex parts on demand presents a solution to traditional challenges such as inventory management, the obsolescence of parts, and logistical hurdles in supplying low-volume or discontinued components. Despite widespread acknowledgment of these benefits, the literature reveals a notable gap: a lack of extensive, empirical studies on the challenges faced in practical applications of digital manufacturing technologies in a real-world SME setting for spare parts production.

Works by Jæger et al. [1] and Cui et al. [3] provide insights into the adoption of AM for spare parts, highlighting its ability to streamline supply chains and reduce lead times. These studies, however, rely on theoretical models or a restricted set of examples, which, while illustrative, do not fully capture the breadth of operational and economic considerations involved in scaling up AM technologies in a practical setting.

The legal right to manufacture spare parts is critical to enabling the production and sale of aftermarket parts. Burns IP Law [2] and Ballardini et al. [13] examine the intellectual property challenges and legal landscapes that surround the additive manufacturing of spare parts. In the United Kingdom, "must fit" and "must match" exemptions to intellectual property law currently play a critical role in enabling the production of aftermarket spare parts as replacement parts, allowing for the repair and refurbishment of various products without infringing the design rights of the original equipment manufacturer (OEM). These exemptions ensure that functional component features, essential for a product to perform its intended purpose "must fit" or, to restore its original appearance "must match" can be manufactured and sold by third parties, fostering competition in the spare parts market. While similar legal frameworks exist in other jurisdictions, the extent to which these exemptions have been tested and interpreted in court varies significantly, leading to a diverse global landscape of enforcement and applicability. This variability underscores the importance of understanding specific national laws and their judicial application when engaging in the production and distribution of aftermarket replacement parts internationally.

Research by Knofius et al. [6] and Verboeket and Krikke [7] addresses the disruptive potential of AM on supply chains, advocating a more localised and flexible production model. Similarly, Top et al. [11] and Ahlsell et al. [12] investigate the sustainability benefits of AM, suggesting that digital manufacturing can contribute to more sustainable production practices, enhancing environmental protection practice by minimising waste and reducing the need for stockpiling spare parts.

The readiness and market demand for digitally manufactured spare parts have been scrutinised by Kretzschmar et al. [4] and Heinen and Hoberg [15], who assessed the maturity of AM technologies and their applicability across different industry sectors. These studies reveal a growing confidence in AM's technical capabilities, and other aspects of suitability for purpose, but also highlight the variability in adoption rates, influenced by sector-specific requirements and economic considerations.

The literature collectively affirms the potential of digital manufacturing in the spare parts industry, yet it consistently points to the absence of comprehensive studies that document the long-term, practical implementation of these technologies. This gap is particularly evident in the context of understanding the economic viability, scalability, and operational impact of transitioning to digital manufacturing methods for a typical SME. This paper aims to enrich the current understanding by providing a grounded perspective on the deployment of digital manufacturing for spare parts, examining the interplay between technological innovation, economic rationality, and operational efficiency in a tangible business environment.

## **1.2 Project Aims**

The primary objectives of the paper are to present an assessment of the feasibility, profitability, payback time, savings, supply chain impact, and sustainability improvements associated with implementing a digital manufacturing cell in a company lacking prior experience in this area. Action research methodology (observing the implementation of a “plan”) has been used within a living lab setting (that is involving a real production setting) to study the effect of introducing AM, and several case studies are presented here for specific aftermarket parts.

Findings have been used to provide a general framework for implementing a digital manufacturing cell for spare parts production.

## **1.2 Living Lab**

A living lab is a real-world testing environment where new technologies, processes, or innovations are developed, implemented, and evaluated in active production settings through collaborative partnerships between manufacturers, researchers, and end-users. The living lab used for this project was based within a company in the United Kingdom that provides refurbishing and repair services for companies with fitness equipment. Prior to this project the company outsourced manufacture of all replacement parts to OEMs or third-party suppliers. The motivation to in-house some production was to help secure supply chains, avoid minimum order quantities, reduce lead times, and increase sustainable business practice.

## **1.3 Service operations**

The company executes the following general steps when delivering on a refurbishment/repair project with a client.

1. Schedule an Engineer to inspect the customer’s equipment.
2. Conduct a repair assessment to generate asset numbers and repair needs.
3. Transport equipment from customer to servicing facility.
4. Strip the equipment.
5. Generate BOM and strip sheet, including any parts that might need replacing.
6. BOM and strip sheet goes to procurement.
7. Procurement decides what parts to manufacture/buy. Orders default to the digital manufacturing team if possible. If the parts are not already in the system, they go to the digital manufacturing team for reverse engineering.
8. PO is sent to the digital manufacturing team and goes into the queue.
9. Parts are manufactured.

10. Manufactured parts are booked in by the parts department.
11. Servicing team takes the parts for refurbishing/repair.
12. Equipment is sent back to the customer.

## **2. Methodology**

Action Research serves as the foundational methodology for this study, facilitating a participatory, cyclical process of planning, action, observation, and reflection. This approach is paramount to addressing the real-world challenges and opportunities presented by the implementation of a digital manufacturing cell. Through iterative cycles of application and evaluation, the Action Research methodology allows for continuous learning and adaptation, ensuring that the digital manufacturing cell evolves in response to practical operational needs and insights gained throughout the study.

In this research Case Study Research methodology has been employed concurrently to conduct an in-depth analysis of specific parts. This approach has enabled a comprehensive examination of the process and outcomes associated with the digital manufacturing cell, encompassing quantitative measures of performance (such as profitability, payback time, and cost savings) and qualitative assessments of its impact on supply chain resilience and sustainability. By focusing on specific cases, the research has provided detailed insights into the practicalities of integrating digital manufacturing technologies in an SME environment unaccustomed to such processes.

The convergence of these methodologies within a Living Lab setting, has provided an example of a real-life, dynamic environment where stakeholders are actively engaged in the innovation process. The living lab is not only the physical space for deploying the digital manufacturing cell, but also the collaborative platform for stakeholders to co-create and test solutions in real-time. This setting has been instrumental in capturing the nuanced and complex interplay between technological implementation and operational practice, offering a rich context for exploring the transformative potential of digital manufacturing technologies.

In practice, the methodology involved a phased approach: beginning with a comprehensive planning phase to design the digital manufacturing cell and its integration strategy, followed by the action phase, where the cell was implemented and iteratively refined based on observed outcomes and stakeholder feedback. Data collection was ongoing, utilizing both quantitative metrics (e.g., production time, cost efficiency) and qualitative feedback (e.g., user satisfaction, perceived improvements in sustainability) to evaluate the system's performance and impact. This blend of methodologies, applied within a living lab environment, ensures a holistic understanding of the digital manufacturing cell's implementation and efficacy, contributing valuable insights to the field of manufacturing systems.

### **2.1 Project plan**

The project was implemented in an SME that is probably representative of a wide range of UK manufacturing businesses. The profile of the business is summarised in table 1.

Table 1. SME business profile (2019).

Number of employees (Graduates)	50 to 250
Number of UK sites	2
Number of overseas sites	0
Approximate annual turnover	£4.9 m

The project was planned in detail from the outset, with clear business objectives in mind that were intended to result from the implementation of AM. Table 2 summarises the aims of each stage.

Project stage	Details	Effort (months)
Stage 0 – Project Inception	Before the project commenced a detailed 2-year project plan was created consisting of five main stages	2
Stage 1 - Assessment	Undertaking a review of technologies and skills required for in-house digital manufacturing, including 3D scanning, CAD software, CAM software, CNC machines and additive manufacturing (AM) equipment. Linking to the company’s current and future business aims of in-house manufacturing and reduced reliance on external supply chains.	4.1
Stage 2 – Trial production run.	The aim of the trial production run is to set up digital manufacturing cells (CNC router, Masked Stereolithography Apparatus (MSLA) and material Fused Filament Fabrication (FFF) 3D printing) to develop the digital production process for a selected portfolio of 15 parts.	5
Stage 3 – Scale up.	Scaling production with an aim of eventually producing all parts identified as manufacturable within the digital manufacturing cell.	9.4
Stage 4 – Future Proofing.	Future proofing and expansion - Review new opportunities that are now possible internally and externally to the company.	1
Stage 5. Dissemination.	Embedding of new knowledge and practices into the company and wider dissemination of findings.	2.5

Table 2. Project stages summary.

Each stage of the project plan allowed for review and evaluation to ensure growth was organic and low risk. A risk register statement was also created to help identify potential risks and how to mitigate them.

## 2.2 Development of the Digital Manufacturing Cells

At the outset of the project two Digital Manufacturing Engineers were employed with Bachelor's degrees in Computer Aided Engineering and Masters qualifications in Additive Manufacturing. As the project progressed the equipment needs were identified, equipment was purchased, and commissioned. Table 1 contains a summary of equipment purchased and the skill set required to run the Digital Manufacturing cells.

Table 3. Equipment and engineering expertise required for implementation of the digital manufacturing cells.

Equipment	Expertise
CKJ-R15 CNC router	Computer Aided Design (CAD)
Photocentric Magna with wash and cure	Design for AM
Ender3 Max	Reverse Engineering
CR-10 S5	Mechanics knowledge
Bambu Lab X1 Carbon Combo	AM experience
Einscan HD with turntable	Computer Aided Manufacturing (CAM)
Laptop	Finite Element Analysis

Figures 1 and 2 shows the final layout of the CNC and AM work cells.

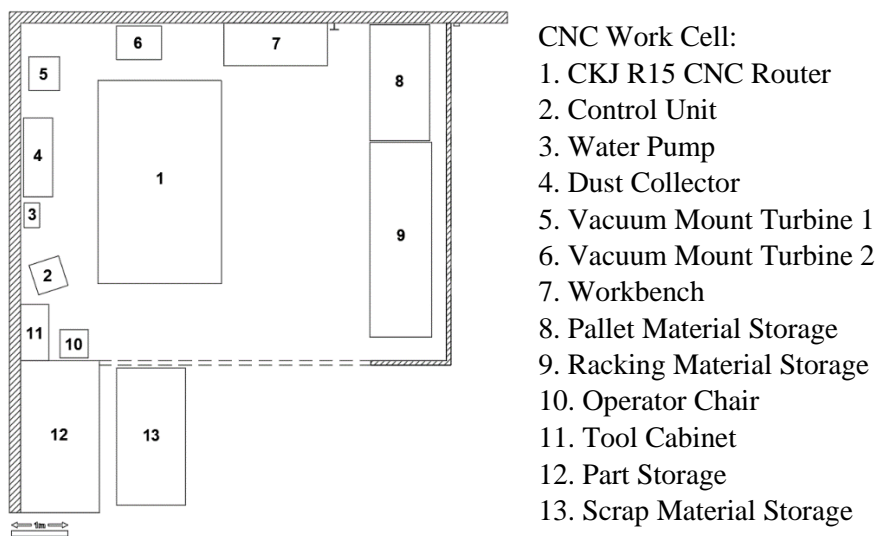


Figure 1. CNC work cell.

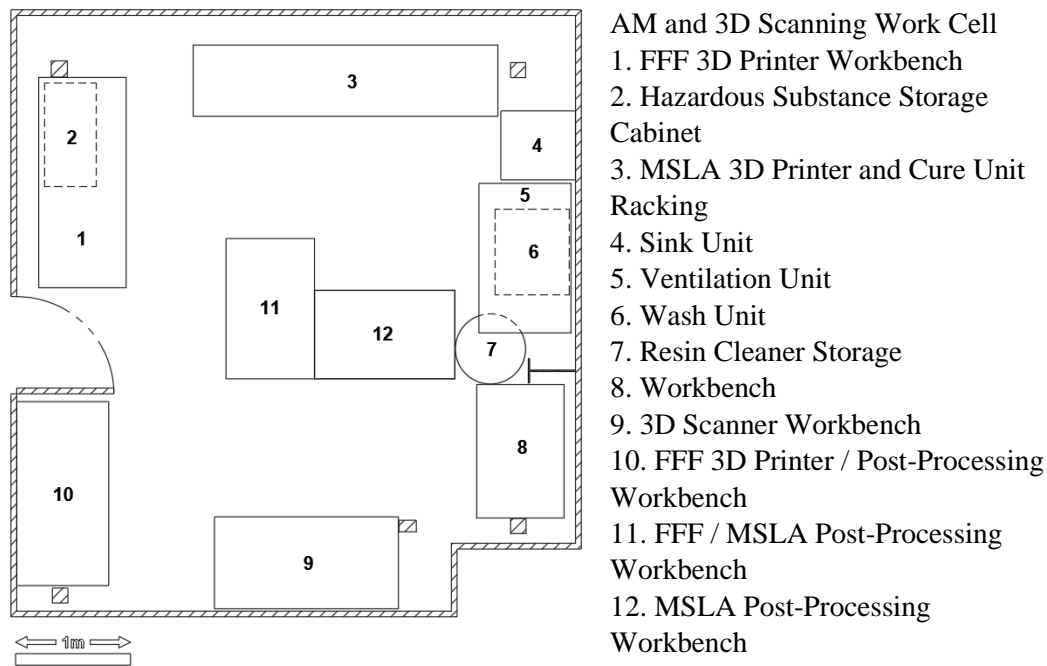


Figure 2. AM and 3D scanning work cell.

### 2.3 Identification of manufacturable components

The number of unique parts held in stock at the start of the project was over 4,036. With the aim of reducing inventory, a rating criterion was developed to help identify the most promising parts to be included in an initial trial production run. The criterion and associated modifying factors were designed to prioritise parts that:

- use easy to process materials,
- are small,
- are expensive to purchase,
- are frequently ordered,
- have low post-processing requirements,
- are non-structural,
- will not be visible during use.
- The modifying factors are shown below:

The rating process used the criteria and parameter values presented in table 4

Table 4. Rating criteria and values.

<b>Control Value</b>	Value assigned as 10 to increase quantitative rating value for ease of ranking.	
<b>Material</b>	Value assigned based on the material's perceived ease of use with the current equipment and/or the likelihood of a	PLA = 1 PETG = 0.9 TPU = 0.5 Nylon = 0.3

	successful manufacturing operation using said material.	Carbon Filled PLA = 0.9 Photocentric Hard = 1 Other = 0.6 Plywood = 1 Phenolic resin = 0.6
<b>Size</b>	Value assigned based on a rough estimate of how long the part may take to manufacture.	≤ 60 mins = 1 ≤ 120 mins = 0.8 ≤ 240 mins = 0.6 ≤ 480 mins = 0.4 > 480 mins = 0.2
<b>Price</b>	Value assigned based on how much each part costs to purchase individually.	Priceless = 1 ≥ 100 = 0.9 ≥ 50 = 0.5 ≥ 10 = 0.3 ≥ 1 = 0.1
<b>Order Frequency</b>	Value assigned based on how much a given part has been ordered within the previous year. Uses the following calculation: Parts Per Order x Orders.	Top Third = 1 Middle Third = 0.6 Bottom Third = 0.2
<b>Post Processing Requirements</b>	Value assigned based on a rough estimate of how much post-processing would be required following manufacturing.	None = 1 Some = 0.6 Lots = 0.2
<b>Structural Load Requirements</b>	Value assigned based on what kind of structural load will be placed onto the part.	Low Load = 1 High Load = 0.5
<b>Aesthetic Requirements</b>	Value assigned based on whether the part will be visible by the customer or hidden within a machine.	Hidden = 1 Visible = 0.5

The data in table was used to evaluate the suitability of aftermarket parts for manufacture by AM using a simple linear quantitative rating (QR) scale.

$$QR = (C \times M \times S \times P \times F \times PP \times SL \times A) \quad \text{Equation 1.}$$

Where: *C*=Control Value, *M*=Material, *S*=Part Size, *P*=Individual Part Cost, *F*=Order Frequency, *PP*=Post Processing Requirements, *SL*=Structural Load Requirements, *A*=Aesthetic Requirements.

## 2.4 Reverse Engineering process

Reverse engineering of the parts was a critically important element of the process. A dimensional assessment of all the original parts was required to meet the basic “must fit”

requirements for the aftermarket parts. For simple parts manually measuring the parts to create parametric CAD models was enough. However, for complex parts 3D scanning was required to first generate a mesh which was then used as a guide for the creation of parametric CAD models of redesigned aftermarket parts with design for manufacture considerations. In some cases changes of material(s) from the original part necessitated iterative experimental evaluation of the durability of re-designed parts to ensure that performance requirements were satisfactorily met.

The reverse engineering process used is outlined in Table 5.

Table 5. Reverse engineering process.

Step	Description
1	Assess complexity of the required part. If simple, manually measure. If complex, 3D scan.
2	Clean, fix and refine the scanned mesh.
3	Convert the mesh to a STEP file using Geomagics.
4	Create a parametric model including any design for AM modifications in Fusion360.
5	Print and test the part for fit and function.
6	Update the model and print parameters based on test performance.
7	Save the CAD and print file in the digital warehouse and enter part information into the CRM system.

### 3. Results and Discussion

#### 3.1 Project timeline

Figure 3 shows a timeline of important events during the project including the purchasing of equipment, hiring of key staff and milestones. One element of significant note is how early in the project the digital manufacturing cell was able to produce the first 5,000 parts. One of the objectives of the project was to ensure utilisation of the new AM was maximised. This was achieved by two approaches, conducting AM work for outside clients, and creating new product lines, not necessarily linked to the existing business. (In figure 3, "external jobs" are defined as manufacturing jobs carried out for external clients rather than parts produced internally for the procurement department and "additional products" are defined as additional items not produced prior to the project.

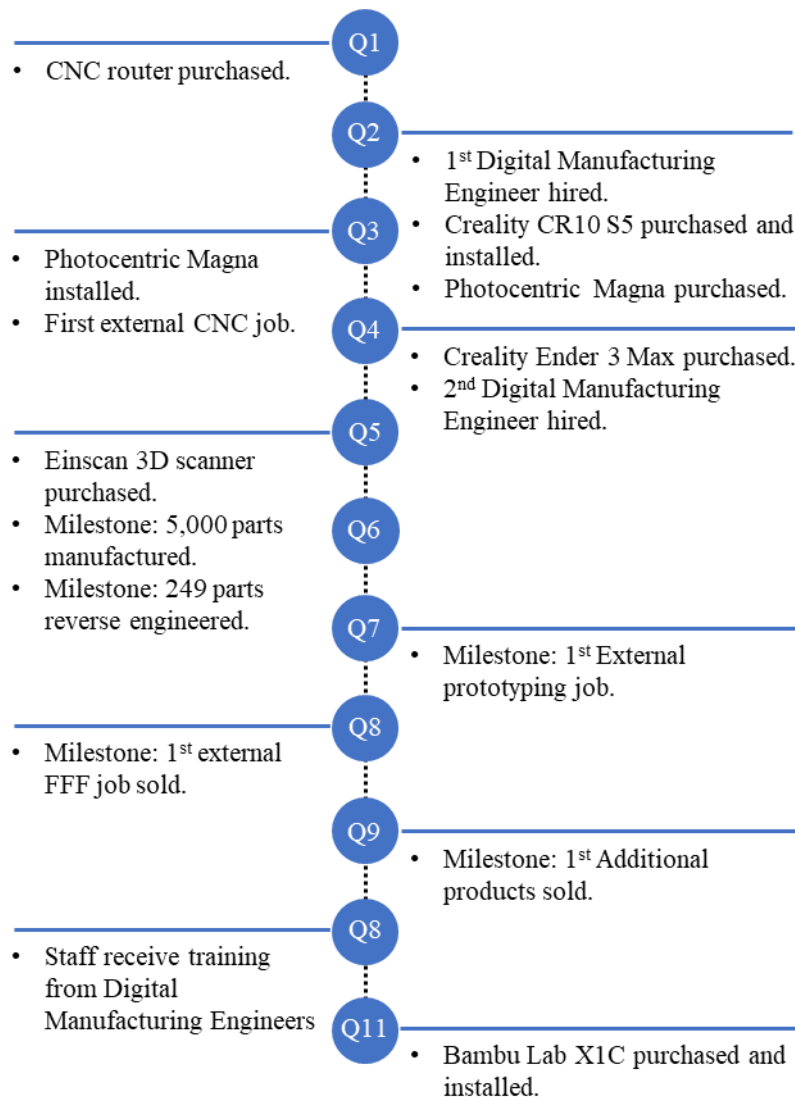


Figure 3. Timeline of key developments.

### 3.2 Reverse Engineering

The requirement to quickly and continuously reverse engineer parts was one of the more challenging operational aspects of the project. Figure 4 shows the number of parts reverse engineered each month varied between 6 and 29. Given the complexity of the scanning process, the mesh repair, modelling, design for manufacture modifications and testing for fit and function involved in this step, it was often the production bottleneck when a new XXX product was first manufactured. However, only one engineer was generally involved in this task at any one time. In the peak months the engineers were reverse engineering a component every 5.7 hours. Over the course of the two-year project the number of parts in the digital warehouse grew to 490, however the need for reverse engineering never diminished. This was due to business growth and the constant introduction of new fitness equipment into the general industry stock. The expected time for a component to be reverse engineered, tested and introduced depends on many factors, however timescales in the region of weeks and

months are not rare. This highlights the importance of the need for highly skilled engineers for situations where frequent rapid reverse engineering is required.

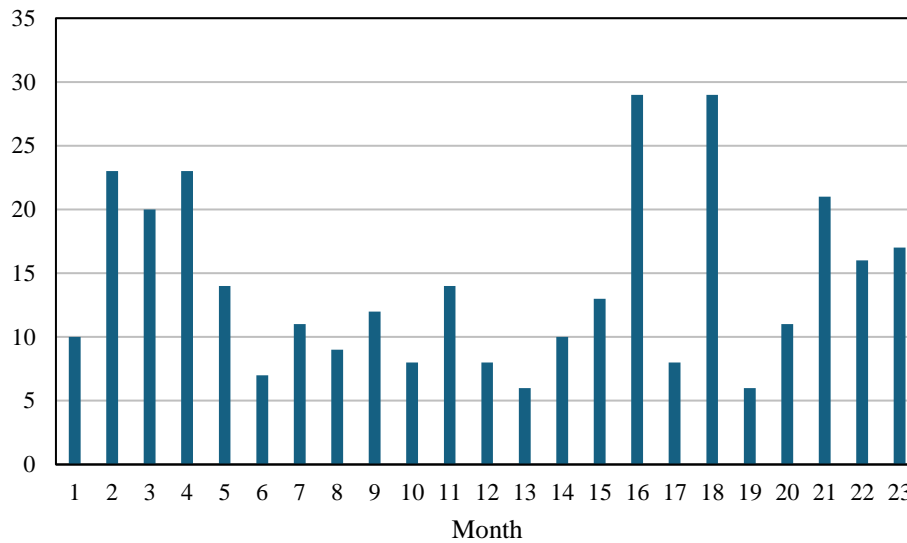


Figure 4. Number of parts reverse engineered each month. Data shown from Q4 onwards.

### 3.3 Part production statistics

Figure 5 presents production data for a full calendar year (Q6 to Q9). The total number of parts produced in this period was 4,530 parts, averaging 84 parts per week with a standard deviation of 76 per week. The most striking feature of the production data is the variability. The demand for spare parts is very difficult to forecast and often results in urgent requests to the digital manufacturing team. This meant the manufacturing cell had to be designed with enough capacity to handle the peaks (but presented challenges relating to ensuring use of “spare capacity” in low demand periods.)

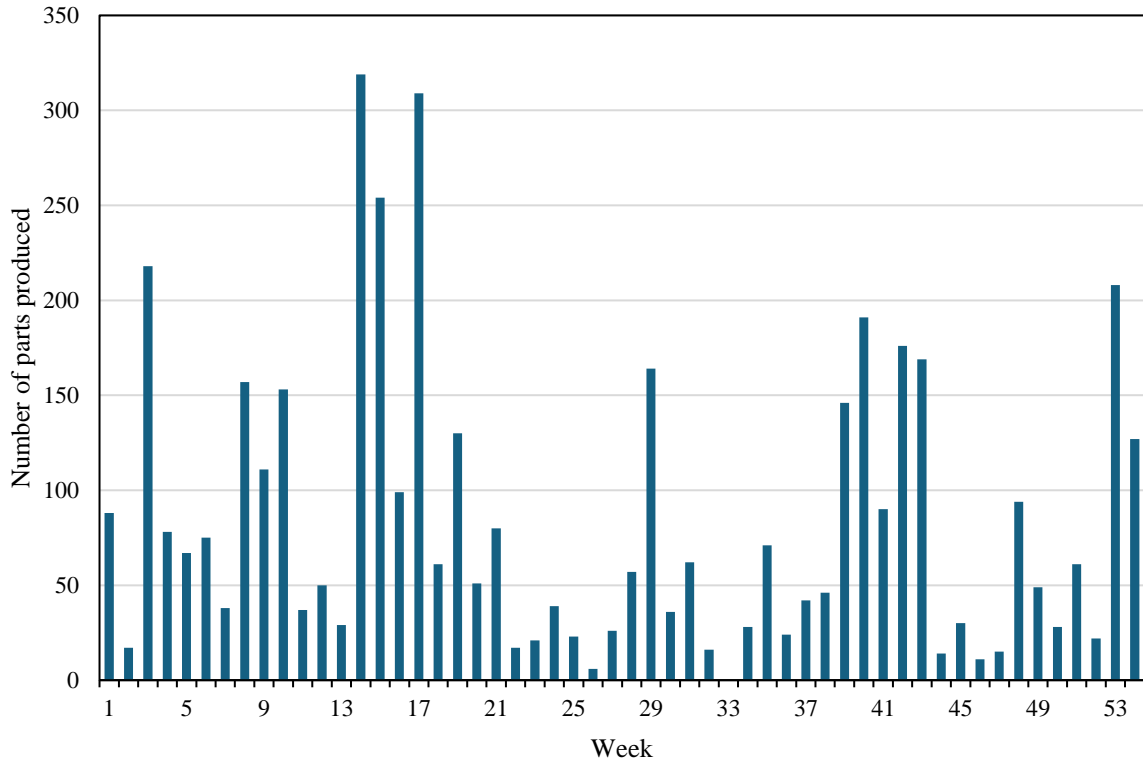


Figure 5. Production data for a full calendar year from Q4 to Q7. Data contains both AM and CNC parts.

Part requests coming from procurement were based on early repair assessments of client equipment and often had lead times on the order of weeks. However, early in the project it became clear that demand for ‘urgent’ parts was higher than expected and a critical function the digital manufacturing department could fulfil. Urgent parts in this context were defined as parts that could not be sourced by any other means within the required time. Contracts with the clients stipulated deadlines for delivery of the serviced equipment with penalties often in place for late delivery. Therefore, the production of urgent parts provided a value to the company considerably in-excess of the simple part cost savings.

Figure 6 presents the cumulative production of regular and urgent parts over time. Urgent parts accounted for 17% of all parts produced. Over the first 18 months of the project the number of parts produced increased almost linearly with around 4500 parts, that would

conventionally have been ordered from a third part supplier, being produced on-site.

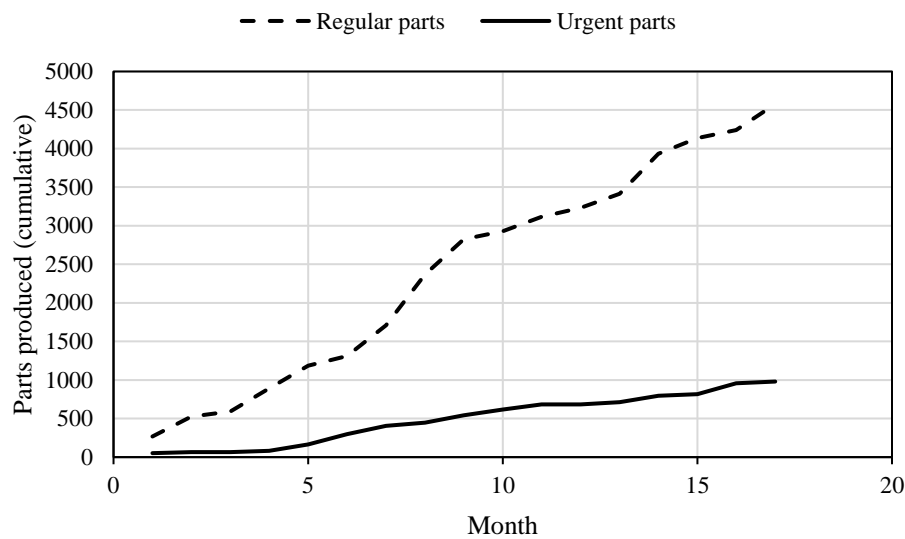


Figure 6. Cumulative part production of regular and urgent parts.

A combination of technologies was used to print the parts. Figure 7 shows the average monthly production numbers for each technology category. The CNC router, MSLA printer and a FFF printer were installed in the first 8 months. The utilisation of the equipment was carefully monitored along with cost saving data. Through this monitoring, it became apparent that the number of FFF machines was insufficient to cope with peak demand, and it was determined from the utilisation data that two additional FFF machines should be purchased to manage the manufacturing workload on this equipment.

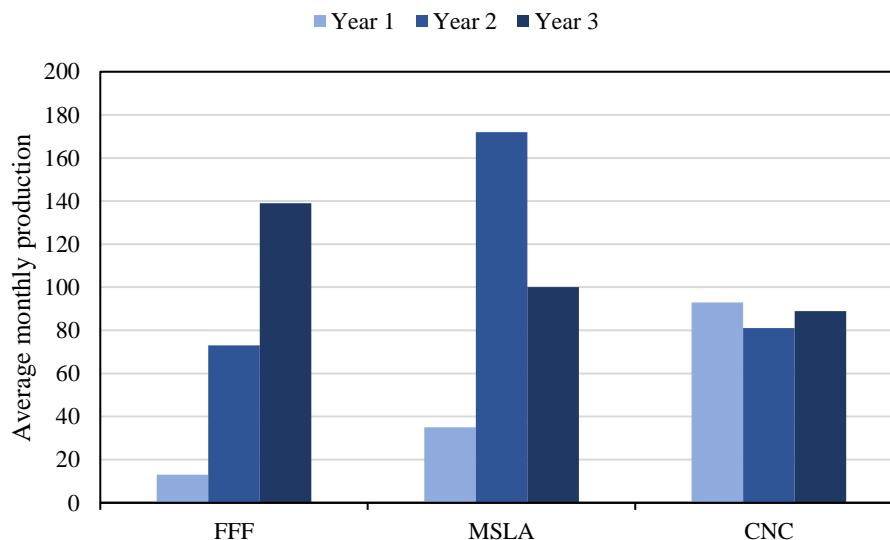


Figure 7. Average monthly part production for each manufacturing process.

### 3.4 Project costs and savings

Production costs for each part were calculated using equation 2.

$$Total\ Cost = (MC + MT + LC + TC + EC) / BS \quad \text{Equation 2}$$

Where: *MC* = Machine cost, *MT* = Material cost, *LC* = Labour cost, *TC* = Tool cost (CNC only), *EC* = External component cost, *BS* = Batch size. Definitions for each of these costs are shown in appendix 1.

Part cost savings were calculated by subtracting the part costs from the cost of externally priced parts at the time of part production. Early expectations were that in-house manufacturing, especially for the 3D printed components, would be more expensive than outsourced parts. This was deemed to be acceptable given the benefits to supply chain security and reduced storage costs. However, this was found not to be the case. Figure 8 shows the part cost savings over one year of production.

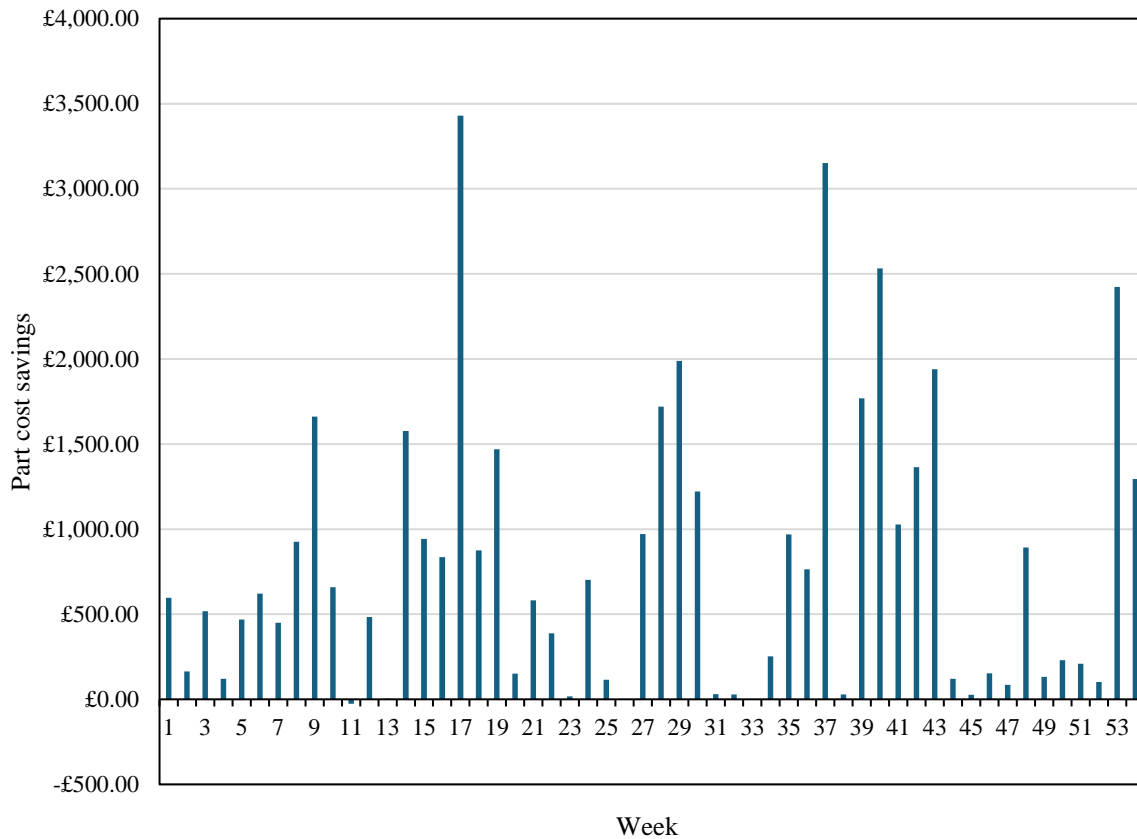


Figure 8. Weekly part cost savings for a calendar year of operation from Q4 to Q7.

Table 6 presents details of the payback time for each of the manufacturing machine types purchased during the project. The payback time is calculated based solely on equipment purchase price, part cost savings and maintenance costs. It was found to range from 1 month for the low cost FFF printer to 19 months for the MSLA printer. Whilst the MSLA printer could produce parts with excellent aesthetic quality, the machine and materials were much more expensive than the FFF printers. The Bambu Lab X1C printer was the most expensive FFF printer. However, it provided the fastest return on investment due to its higher print speeds, more advanced features and an Automatic Materials System (AMS).

Table 6. Equipment cost with payback time and maintenance costs.

Plant Equipment	Purchase Price EX VAT	Pay Back Duration	Maintenance Cost Per Year
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CKJ R15 CNC Router	£15,700.00	9 Months	£606.96
CR10 S5 (FFF)	£550.00	3 Months	£150.00
Ender 3 Max (FFF)	£150.00	2 Months	£150.00
Bambu Lab X1C (FFF)	£1,099.00	1 Month	£150.00
Photocentric LCD Magna Bundle (MSLA)	£24,000.00	19 Months	£214.24

#### 4. Case studies

The following three case studies of aftermarket component development and manufacture highlight how a range of manufacturing challenges encountered during the project were met.

##### 4.1 Power supply box cover

This component is a reverse engineered and modified Power Supply Box Cover (Figure 9), which is part of the power supply/inlet unit for a treadmill.

Experience showed that much of the time, only the polymer cover of the assembly was found to be broken on equipment submitted for servicing. Conventionally, as the parts for the assembly are not available separately, the entire sub-assembly with all electronics included would have to be purchased, meaning a significant cost investment for replacing a single polymer part and sometimes the unnecessary wastage of working components.

Manufacturing data for this part is presented Table 7 below.

Table 7. Power supply box cover manufacturing data

Machine:	Photocentric Liquid Crystal Magna
Material:	Photocentric Daylight Magna Resin Hard Black
Manufacturing Batch Size:	18
Manufacturing Time:	22 hours 02 minutes
Cost to Manufacture (Per Part):	£15.91
Cost to Purchase New (Whole Assembly):	£200.40
Cost Saving:	£184.49

The polymer cover was reverse engineered and partially redesigned to meet “needs to fit” criteria. Manufacture of this single part reduced costs and order times directly, better suiting the needs of the partner company. The partner company logo was also added to the inside of the part to allow identification in future.



Figure 9. Left: Original assembly. Right: Printed replacement part.

#### 4.2 Roller end cap

A Roller End Cap (Figure 10), is part of a larger assembly which consists of an inner tube, foam, vinyl covering, one to two end caps and one to two end cap covers.

It was found that on serviced equipment, only the end caps of the roller would generally be damaged and require replacement. However, as in the case of the power supply cover the parts are not sold separately, and the entire roller pad assembly would normally have to be purchased as replacements. Buying all these parts costs significantly more than just replacing a single end cap and meant that the rest of the components from the damaged roller would either be wasted or simply cannot be used until another damaged roller comes in. Manufacturing data for the roller end cap can be found in Table 8 below. The cost saving associated with direct manufacture of this part are significant.

Table 8. Roller end cap manufacturing data.

Machine:	Bambu Lab X1 Carbon Combo
Material:	1.75mm PLA Filament
Manufacturing Batch Size:	2
Manufacturing Time:	09 hours 43 minutes
Cost to Manufacture (Per Part):	£11.76
Cost to Purchase New (Whole Assembly):	£80.64
Cost Saving:	£68.88



Figure 10. Left: Original assembly. Right: Printed replacement part.

#### 4.3 Phenolic resin top deck

The phenolic resin top deck (Figure 11), is part of a larger two-part deck assembly consisting of a 25mm High Density Fibreboard (HDF) deck and the 3mm phenolic resin top deck used in a treadmill (running machine).

Frequently, when decks were removed from treadmills submitted for servicing the phenolic top deck exhibited wear that interfered with proper operation of the treadmill belt but leaving the HDF undamaged. With the increasing price of wood in recent years it became very expensive to replace the deck assembly. Replacing just the phenolic resin top deck with a reverse engineered component proved to be a viable option as it was possible to reposition the screw holes to reuse the original HDF sheet. Again, cost savings resulting from manufacturing this part on-site were very significant.

Table 9. Phenolic resin top deck.

Machine:	CKJ R15 CNC Router
Material:	3mm PF CP 201
Manufacturing Batch Size:	2
Manufacturing Time:	45 minutes
Cost to Manufacture (Per Part):	£44.77
Cost to Purchase New (Whole Assembly):	£138.72
Cost Saving:	£93.95



Figure 11. Left original assembly. Right: Machined replacement part.

## 5. Discussion

### 5.1 Framework for implementation

A framework for implementing a digital manufacturing system for aftermarket parts production has been developed based on the experience gained during this project and with the benefit of hindsight. Figure 12 outlines the phased approach. Each step of the flowchart highlights the key decisions, investments, and processes involved, from inception to production integration, scaling, and future growth.

This structured representation is presented as a model which can be adopted by SMEs in developing digital manufacturing cells for component production. It is generalised and can be applied equally for the development of facilities for the manufacture of OEM parts and for aftermarket parts. It is intended to provide a structure which gives insight into the logical progression and interdependencies between phases. Examples of some of the main challenges faced when implementing digital manufacturing following the sequence in Figure 12 are discussed below and these issues should be addressed in parallel to the application of the model outlined.

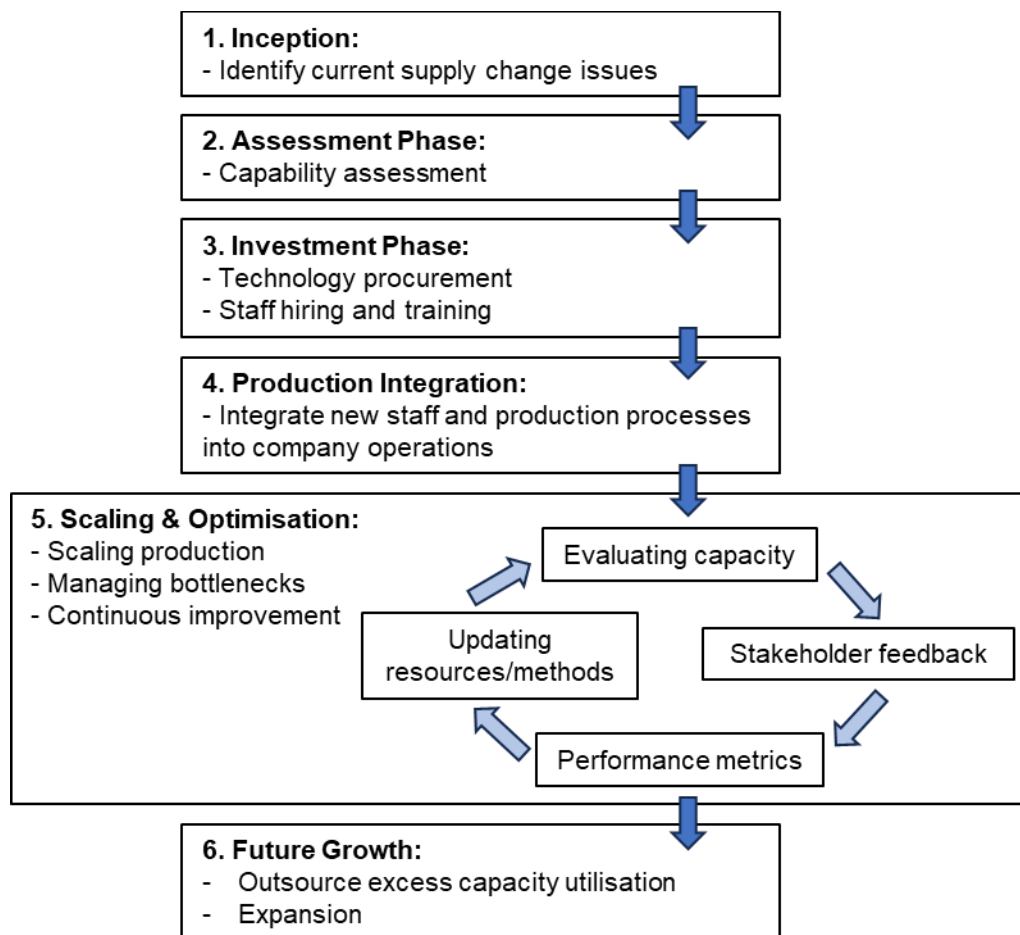


Figure 12. Model for the implementation of a digital manufacturing cell in an SME.

## 5.2 Lessons Learnt

This project confirmed that digital manufacturing processes, including additive manufacturing are technically and economically feasible processes to produce spare parts in a company with no prior digital manufacturing experience. A key criterion for success is to introduce new employees with a skill set that matches the requirements of a digital manufacturing environment. In this project master's graduates with direct experience of reverse engineering, CAD and additive manufacturing were selected to fulfil this role.

The method for identifying which parts should be selected for in-house manufacture, outlined in section 2.3 was ultimately not as useful as originally anticipated. Whilst the formula was effective for down selecting the most economically manufacturable parts, the most urgent

requests from the “shop floor” were found to be for parts outside this short list. It soon became clear that building the digital warehouse with a just in time strategy was the best way to react to the uncertain demand.

One of the most important unforeseen benefits of in-house manufacture was the ability to repair sub-assemblies for which the sub-components could not be purchased individually. This not only offers considerable cost savings but is also represents a more sustainable option.

Manufacturing parts on-site provided opportunities for enhanced marketing and brand recognition. The company often placed their own logo on the parts, but clients could also request their logos to be added, leading to improved client satisfaction.

Several new products were developed and added to the company online store. The aim was to develop an extra income stream and generate additional products that would increase printer utilisation during dips in demand. This initiative had minimal success over the duration of the project. Whilst a few parts sold, it was expected not to be a profitable strategy for the future due to the associated design and overhead costs.

A number of improvements in the sustainable operation of the business automatically followed from change in practice to in house manufacture. Additionally, through a relationship with the university partner, failed FFF prints and support structures were donated for recycling. This improves the sustainability of operation whilst reducing carbon emissions and waste disposal costs.

The company attributed a 6% increase in profits (equivalent to £ 294,000, annually) to the new digital manufacturing capabilities and are planning to replicate the strategy at their overseas sites in Europe and Saudi Arabia.

### **5.3 Bottlenecks and Barriers to Expansion**

At various times, the reverse engineering, additive manufacturing, and post-processing were all bottlenecks in the production process. This is not surprising given that the attempts to accommodate the unplanned demand on the new service. The nature of the business environment also led to extreme variability in the types and number of parts needed at any one time. It is anticipated that as the new system becomes more established, bottlenecks will be reduced, especially as some activities such as reverse engineering will tend to be less frequent.

Reverse engineering is currently a high skill and labour-intensive task. As the digital manufacturing team only had two members, they were involved in all the production tasks. Improvements in the efficiency of this unit could be made by training technician staff to run the printers and carry out the post-processing, leaving the digital manufacturing engineers to conduct more time demanding higher-skill level reverse engineering tasks.

The specifications and capabilities of the new equipment purchased for the development were also a factor contributing to the efficiency of parts delivery. Only low-cost AM technologies were forecast to have sufficiently fast payback time to provide confidence in the capital expenditure. The slow print speeds, small build volumes and low reliability all contributed to

limit the size of parts that could reasonably be printed. For example, during the project a large-scale (~1m wide) PlayStation controller was printed for marketing purposes, which took 100% of the capacity of one FFF printer for 5 weeks. The printers used in this study were limited to polymers, so no metal components could be printed. Forecasts suggested metal 3D printing would not be profitable within the current business model. Reduced equipment and material costs would help lower the barriers to further adoption of AM technology.

Post processing of parts is generally a very manual process and can be time consuming. Parts often needed to be trimmed to remove brims and support structures and blemishes sanded. MSLA parts also need to be washed and cured. There is a need for higher levels of automated material handling and quality control to improve machine utilisation and to reduce labour costs. This is supported by literature stating AM has been studied from a flexibility dimension with less research into automation of its implementation [17]. Table 10 summarises the project findings in the form of a SWOT analysis.

Table 10. SWOT analysis of project findings.

Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• <b>Rapid Integration:</b> Digital manufacturing cell became operational within a short timeframe.</li> <li>• <b>Cost Savings:</b> Significant cost reductions by in-house production of spare parts compared to outsourcing were demonstrated.</li> <li>• <b>Flexibility:</b> Urgent demands were met through agile manufacturing practices, reducing lead times significantly.</li> <li>• <b>Scalability:</b> A modular approach to scaling production allowed for seamless expansion in capacity.</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Skill Gaps:</b> Limited availability of talent with expertise in reverse engineering and additive manufacturing, could lead to difficulties hiring staff at an affordable price point.</li> <li>• <b>Initial Production Bottlenecks:</b> Challenges in reverse engineering of complex parts caused delays during the initial production phase.</li> <li>• <b>Variable Demand Management:</b> Managing peaks and troughs in demand required maintaining excess machine capacity, leading to inefficiencies.</li> </ul>
Opportunities	Threats
<ul style="list-style-type: none"> <li>• <b>New Market Segments:</b> Potential to expand digital manufacturing capabilities to other industries with similar spare parts needs.</li> <li>• <b>Technology Integration:</b> Leveraging IoT and data analytics to improve predictive maintenance and optimise production processes.</li> <li>• <b>Sustainability:</b> Using recycled materials and minimising inventory enhanced the company's environmental profile.</li> <li>• <b>Training and Upskilling:</b> Establishing training programs for existing employees will create a highly skilled workforce that is resilient to technological changes.</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Supply Chain Vulnerabilities:</b> Dependence on specific raw materials for 3D printing could be impacted by supply chain disruptions.</li> <li>• <b>Technological Obsolescence:</b> Rapid advances in manufacturing technology may require frequent upgrades to maintain competitiveness.</li> <li>• <b>Regulatory Challenges:</b> Changes in intellectual property laws could limit the ability to produce certain spare parts, affecting business operations.</li> <li>• <b>Competition:</b> Other firms adopting similar digital manufacturing strategies may erode competitive advantage over time.</li> </ul>

## 6. Conclusion

The implementation of a digital manufacturing cell for spare parts production in the fitness equipment restoration industry has demonstrated significant potential for transforming traditional supply chain models. Our findings reveal that in-house digital manufacturing not only provides substantial cost savings but also offers critical advantages in terms of supply chain resilience, lead time reduction, and sustainability.

Key outcomes of the study include:

- Rapid integration and scaling of digital manufacturing capabilities, with over 4,500 parts produced in the first full year of operation.
- Significant cost savings across various part types, with some components showing up to 92% reduction in cost compared to traditional sourcing.
- Quick return on investment for most equipment, ranging from 1 to 19 months, demonstrating the economic viability of the approach.
- Enhanced ability to meet urgent production demands, with almost one fifth of parts produced addressing critical needs that could not be met through traditional supply chains.
- Development of a robust reverse engineering process, capable of digitizing up to 29 new parts per month, highlighting the importance of skilled engineering in this domain.

The case studies presented illustrate the versatility of digital manufacturing in addressing diverse challenges, from complex polymer parts to phenolic resin components, showcasing the technology's adaptability across various materials and geometries.

The study also highlights ongoing challenges, particularly in managing variable production demands and the continuous need for rapid reverse engineering capabilities. These findings underscore the importance of flexible manufacturing systems and highly skilled personnel in successfully implementing digital manufacturing for spare parts.

In conclusion, this research has provided empirical evidence supporting the viability and benefits of integrating digital manufacturing technologies for spare parts production. It offers valuable insights for industries considering similar transitions, emphasizing the potential for cost reduction, improved supply chain responsiveness, and sustainability. Future activities in this project should focus on further optimizing production planning for variable demands and exploring the long-term impacts on inventory management and overall business models in the spare parts industry.

### **CRedit authorship contribution statement.**

**Hadley Brooks:** Conceptualisation, Funding Acquisition, Methodology, Supervision, Writing - Original draft, Writing - Review and editing. **Ruben Janse van Vuuren:** Formal analysis, Methodology, Visualisation, Writing - Original Draft, Writing - Review & editing. **Emily Miller:** Formal analysis, Methodology, Visualisation, Writing - Original Draft, Writing- Review & editing. **Ian Sherrington:** Funding Acquisition, Supervision, Writing – Review and editing.

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Appendix:

Part production cost calculations.

$$MC = \left( \left( \frac{MP}{MRHPY} \right) + IPH + OPPH \right) \times PT$$

$$OH_{CNC} = \left( \frac{YMC + \left( \frac{SC_1}{NMPS_1} + \frac{SC_2}{NMPS_2} + \dots \right)}{MRHPY} \right) + FAIPH + HPC + HSC$$

$$OH_{LCD} = \left( \frac{YMC + \left( \frac{SC_1}{NMPS_1} + \frac{SC_2}{NMPS_2} + \dots \right)}{MRHPY} \right) + FAIPH + OEIPH + HPC + HSC$$

$$OH_{FFF} = \left( \frac{YMC + \left( \frac{SC_1}{NMPS_1} + \frac{SC_2}{NMPS_2} + \dots \right)}{MRHPY} \right) + HPC + HSC$$

$$LC = OL + DL$$

$$TC = \frac{TP}{ATL}$$

$$Total\ Cost = \frac{MC + MT + LC + TC}{BS} + EC$$

Where:

MC = Machine costs, MP = Machine Price, MRHPY = Maximum running costs per year, IPH = Interest per hour, OPPH = Overheads price per hour, PT = Print time, OH<sub>CNC</sub> = Overheads (CNC), YMC = Yearly maintenance costs, SC<sub>1</sub> = Software cost, NMPS = Number of machines per software, MRHPY = Maximum running hours per year, FAIPH = Financial agreement interest per hour, HPC = Hourly power costs, HSC = Hourly storage cost, OH<sub>LCD</sub> = Overheads (LCD), OEIPH = Other equipment interest per hour, OH<sub>FFF</sub> = Overheads (LCD), LC = Labour costs, OL = Operator labour costs, DL = Designer labour costs, TC =

Tool cost (CNC only), TP = Tool price, ATL = Average tool life, MT = Material cost, EC = External component cost, BS = Batch size