BEYOND TECHNOLOGY – AN INTERDISCIPLINARY APPROACH TO ACCELERATING VALUE RETENTION ADOPTION IN HIGH-INTEGRITY SECTORS

Stephen Fitzpatrick − University of Strathclyde (National Manufacturing Institute Scotland)
Andreas Reimer − University of Strathclyde (National Manufacturing Institute Scotland)
Calum Hicks − University of Strathclyde (National Manufacturing Institute Scotland)
Syed Munawar − University of Strathclyde (National Manufacturing Institute Scotland)

Abstract
Achieving circularity in high-integrity sectors such as aerospace, wind energy, and power generation requires more than technological innovation alone. The University of Strathclyde's National Manufacturing Institute Scotland (NMIS), in partnership with the UK Government, and industry partners, is leading two major projects: ReMake Glasgow and the ReMake Value Retention Centre. These projects recognise that maximising the circular opportunity for high-integrity sector products demands a system-wide, interdisciplinary approach and cross-sector learning.

This paper presents a case study focused on energy compressor systems, where advanced manufacturing technologies were integrated with a supportive business model and enhanced digital traceability systems to enable new remanufactured products. High-Pressure Cold Spray (HPCS), Laser Cladding (LC), and High-Velocity Oxygen Fuel (HVOF) thermal spray were extensively trialled and benchmarked against the existing hard chrome coating. These trials delivered a 9-fold improvement in wear resistance, a 3-to-4-fold increase in low-cycle fatigue life, and a 17% reduction in manufacturing costs.

A servitisation business model was developed to support and scale these advancements, shifting from traditional product sales to service-based offerings. In parallel, a Digital Product Passport (DPP) system was implemented to enhance traceability during manufacture and remanufacture of the product to support lifecycle management. By implementing both of these systems additional benefits can be realised, such as through the monetisation of data for the aftermarket teams, or by empowering insights into in-service damage modes. This holistic approach has created the conditions necessary to accelerate circularity in high-value sectors where durability, safety, and performance are paramount, providing opportunities for cross-sector learning and adoption.

Introduction and Motivation
The global push towards sustainability and circular economy principles has gained significant momentum in recent years, driven primarily by environmental concerns and resource scarcity [1]. High-integrity sectors such as aerospace, wind energy, and power generation, face unique challenges in adopting Circular Economy (CE) practices due to their stringent safety and performance requirements, complex supply chains, and long product lifecycles [2].

Recognising the need for a comprehensive approach to circularity in these sectors, the University of Strathclyde's National Manufacturing Institute Scotland (NMIS) has embarked on two innovative projects: ReMake Glasgow and the ReMake Value Retention Centre. These initiatives, with a combined investment of £15 million, aim to revolutionise the way high-integrity sectors approach product lifecycle management and value retention. The motivation behind this research stems from the realisation that technological advancements alone are insufficient to drive the systemic changes required for true circularity. While innovative manufacturing techniques and materials play a crucial role, they must be complemented by new business models, digital infrastructure, and cross-sector collaboration to create a holistic ecosystem that supports circular economy principles.

The work presented in this paper investigates a broad manufacturing challenge to source alternatives to electroplated hard chrome (EHC), which has seen widespread use to provide a wear and corrosion resistant coating in high-integrity steel parts, such as for journal bearings of compressor rotors [3, 4]. Policy is being introduced in the UK, EU, and USA to restrict the manufacture of EHC due to the toxic and carcinogenic feedstock necessary in its manufacture [3,

4]. Therefore, there is a widespread need to source and validate alternative coatings, and an associated opportunity to align the validated manufacturing solution with circularity principles and benefits. In the paper, we demonstrate how an interdisciplinary approach, as shown schematically in Figure 1, can accelerate the adoption of value retention practices in high-integrity sectors. Other interdisciplinary areas where considered, as listed in Table 1, but they did not have a material impact on the application going into service. Therefore, they were omitted from the study.

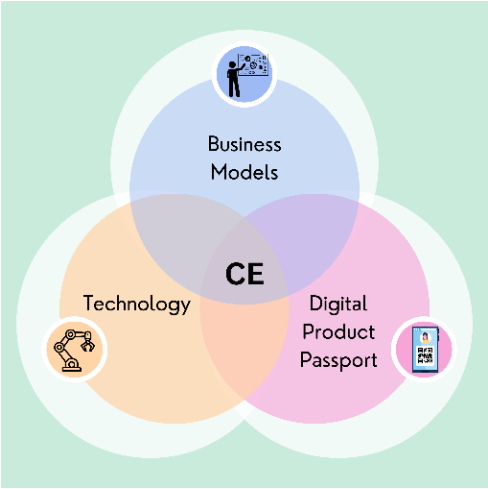

Figure 1 – High level schematic of the interdisciplinary approach implemented in this work

Table 1 - Interdisciplinary focus and other considerations

Category	***Description***	***Reason for Focus***	***Focus Level***
Business Models	Developing new models for value capture, emphasising reuse, sharing, and extending product lifecycles.	Enabled economic incentives for remanufacturing by shifting to service-based contracts and aligning profitability with sustainability.	Primary focus
Technology / Process	Innovations in remanufacturing technology and processes to enable efficient reuse and product renewal.	Provided essential advancements (e.g., High-Pressure Cold Spray) for durability, cost savings, and production scalability.	Primary focus
Data, AI and Digital Product Passport	Leveraging data and AI to predict maintenance, track product lifecycles, and optimise remanufacturing.	Supported data-driven decision-making, enhanced lifecycle traceability, and provided actionable insights for optimisation.	Primary focus
Design	Creating products designed for remanufacture, focusing on durability, modularity, and recyclability.	Ensured compatibility with remanufacturing process, improving product lifecycle and reducing waste.	Supportive
Supply Chain	Configuring supply chains to enable circularity, material recovery, and remanufacturing logistics.	Supply chain integration was not a challenge as remanufacturing was managed internally, simplifying logistics.	Supportive
Standards	Establishing guidelines to ensure quality and consistency in remanufacturing practices.	Standards were already established, requiring minimal adjustments for this specific remanufacturing application.	Supportive
Economic	Highlighting cost savings and financial benefits to companies adopting remanufacturing.	Economic benefits were recognised as a natural outcome of extending product lifecycles and reducing material costs.	Outcome
Environmental	Reducing waste and resource use through remanufacturing practices.	Environmental impacts were inherited outcomes of the remanufacturing approach but not areas requiring active intervention.	Outcome
Social / Culture	Promoting societal awareness and cultural shifts towards remanufacturing adoption.	Social and cultural changes were considered longer-term effects, not immediate business priorities for this project.	Outcome

Review of Related Work

Current linear economy business models rely on high turn-over of new products to provide revenue and is more prevalent for already established manufacturing companies [5]. However, circular business models are well understood, particular in the form of PaaS (Product-as-a-Service), in which consumers pay per unit of service through long-term contracts. Servicing, spares, and repair are all generally included by the product manufacturer as part of the long-term *servitisation* contract [6]. One of the leading high-integrity examples of this can be seen in the servitisation contract provided for Rolls-Royce engines in which the risk of owning an engine was shifted from the customer to the manufacturer [7]. With the sales of spare parts forming a large part of their revenue, the shift to a business model dominated by servitisation contracts incentivised Rolls-Royce to produce durable, high-integrity products: a clear benefit for the customer [7].

Servicing, repairing and remanufacturing are fundamental activities to a servitisation business model. Therefore, design for remanufacturing and advanced manufacturing technologies, such as additive manufacturing and coating technologies are seen as key enablers to help deliver a CE [8, 9]. These technologies have the capability to streamline supply chains [8], support minimisation of manufacture waste [9], and are capable to repair and remanufacture existing components [8, 9]. In the context of the case-study investigated in this work, several coating technologies have been touted to produce alternatives to EHC, such as laser cladding [10], high-velocity oxygen fuel thermal spray [3], and high-pressure cold spray [11]. However, building a framework to reliably restore worn and damaged coatings repeatedly over the lifetime of a servicing contract requires digital architecture to ensure quality and compliance.

The European Union is introducing the Digital Product Passport (DPP) as part of its Green Deal to promote CE within the European Single Market [12, 13]. The purpose of the DPP is to enhance transparency and sustainability by providing comprehensive information about a product's lifecycle, including its origin, materials, environmental impact, and disposal recommendations [14]. The open data principles and structure aim to improve supply chain management, ensure regulatory compliance, and support companies in identifying and mitigating risks related to authenticity and environmental impact [15]. Therefore, the DPP is a key requirement of the digital infrastructure required to deliver CE.

As laid out by Sakao et al. [6], manufacturers can discretise CE activities into two broad categories: the business model, and the product lifecycle. They propose that these should be developed in parallel and not independently due to complexities in their interrelationship. Many companies already have legacy processes, technologies, and practices that are designed to thrive in a linear economy, particularly those in the high-integrity sector, meaning that an isolated approach to CE activities is often impractical. Instead, a holistic interdisciplinary approach, in which the transformation to CE can be better realised is required, aiming to prevent a narrow vision that risks producing an ineffective solution [6].

Technology Approach

In this section, the different areas of the Venn diagram, presented in Figure 1 are discussed in more detail, accompanied by a relevant case study of a shaft remanufacture on a compressor rotor. This can be seen in Figure 2b. In Advanced Manufacturing Techniques, it is discussed how key technologies such as Cold Spray can be used to manufacture and remanufacture components. Followed by the Digital Product Passport, which expands on the developed framework and its implementation to a manufacturer. Lastly, this section will touch on the developed business models and its multifaceted considerations for businesses to implement.

Advanced Manufacturing Techniques

In the 100-years that EHC has been on the commercial market, coating technologies and materials have seen significant innovation. Based on the specific requirements of the compressor rotor journal bearing, three different coating technologies were down-selected and trialled for alternative coatings, with their properties benchmarked against the existing hard chrome coating: High-Pressure Cold Spray (HPCS), Laser Cladding (LC), and High-Velocity Oxygen Fuel (HVOF) thermal spray. Key considerations were matching or improving on mechanical performance metrics, such as wear-resistance and fatigue-performance, providing sufficient manufacture productivity to deliver their annual part turnover, and reducing manufacture costs. Despite the focus of this work to replace the EHC on the rotor journal bearing, a further consideration was made to evaluate the flexibility of the technology to also enable repair and remanufacture of other parts within the compressor component, such as nickel plating on the rotor casings.

Based on the aforementioned criteria, it was determined that a tungsten-carbide cermet material deposited with HPCS technology was the most appropriate. HPCS is a solid-state deposition that can create dense, strongly bonded coatings and bulk material. A process gas, such as Nitrogen is delivered into a chamber in which it is heated and pressurised in the range of 300 – 1100 °C and 10 - 60 Bar respectively. The gas is then mixed with a powder feedstock and ejected through a converging-diverging (De-Laval) nozzle. As the powder particles impact the substrate, there is a rapid exchange of kinetic energy into localised plastic deformation. The material can be built in an additive layer-by-layer fashion with a robotic manipulator to position the stream. Despite the high temperature of the process gas, the short exposure time of the powder and the temperature conversion to kinetic energy during transit through the nozzle, results in a solid-state process (i.e., below the melting point), which minimises heat degradation of the substrate and undesirable metallurgical phase transformations. Furthermore, the peening effect from the impact of powder particles develops compressive stresses that are beneficial for adhesion and fatigue performance.

Optimised for HPCS, the coating consists of a blend of two feedstock powders. To provide superior hardness and wear resistance, a tungsten-carbide cermet has been selected. However, by itself, tungsten-carbide cermets are generally incompatible with the cold spray process because they lack sufficient ability to plastically deform. Therefore, to increase the overall deposition efficiency and ductility, a nickel 'binder' phase was sprayed simultaneously. The two-phase structure formed in the coating can be seen in Figure 2c-d, in which the tungsten carbide particles can be seen homogeneously distributed throughout the nickel matrix.

Wear testing was conducted using a TRB3 Anton Paar tribometer with a alumina sphere ball. Tests were conducted in both the dry conditions and as well as under lubricated conditions using VG68 lubricating oil. For rotary bending fatigue testing, coatings of minimum 200 µm thickness were applied using the EHC and CS on parallel gauge cylindrical coupons of 5.5 mm diameter, and then subsequently cylindrically ground back to a final diameter of 5.7 mm and 0.2 Ra. Testing was conducted using a R.R. Moore rotary bending fatigue testing system with localised air cooling and a test frequency of 10 Hz. Two loading conditions were tested and replicated with three samples per load. Finally, cost modelling was conducted to compare the financial burden of continuing to outsource their EHC coatings or insourcing the HPCS solution. The model incorporated the annual plating requirements across the entire product family. Feedstock and gas costs, coating velocity speeds, heat-up and cool-down cycles and overall cell productivity has been derived from the development trials conducted through this work. Pre-processing and post-processing was assumed to be consistent with current procedures in place for EHC, but with higher performance grinding wheels.

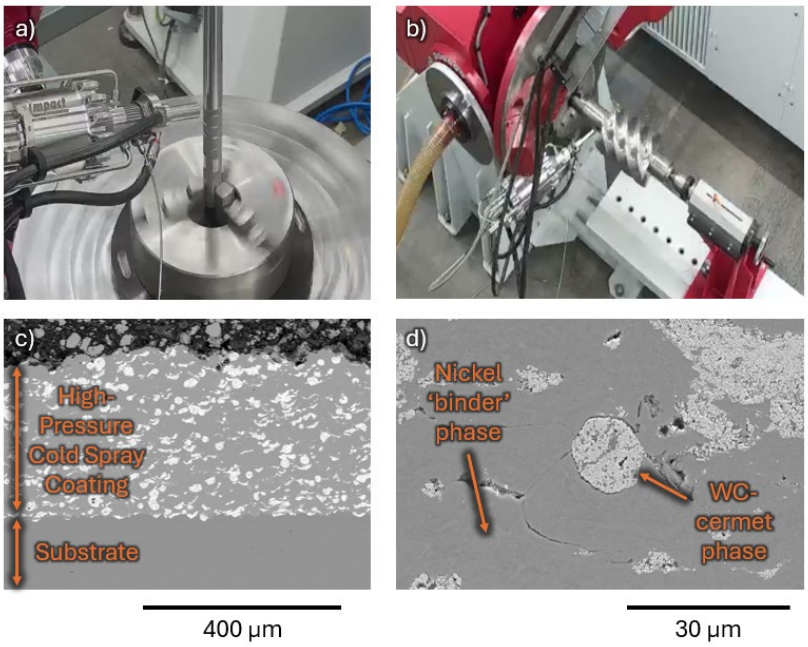

Figure 2 – High Pressure Cold Spray (a) coating trial development, (b) manufacture trials on a rotor component, (c) micrograph of the coating cross-sectional structure, and (d) at a higher-magnification

Compared with the existing EHC coating, the HPCS coating developed in this work delivered:

- **a 9-fold improvement on wear resistance**, translating to substantially longer component lifespans and reduced maintenance requirements.
- **a 3-4-fold improvement in low-cycle fatigue life**, indicating greater reliability and longevity.
- **>17% reduction in manufacturing costs**.

Continuing developmental work is expected to further assess and optimise the deposition efficiency, coating adhesion, galling behaviour, and high-cycle fatigue performance.

Digital Product Passport

The NMIS ReMake Digital Product Passport (DPP) framework, illustrated in Figure 3, was developed during the project to assist companies in assessing key steps when developing a DPP offering for their products. Companies that want to explore DPP would start at Level 1, business drivers. This is where business leaders would look at how the Ecodesign for Sustainable Products Regulation (ESPR) impacts the high-integrity sector, the digital capability of the organisation, data security requirements, and the value of DPPs to the organisation. The compressor sector is presently unaffected by the ESPR Act; however, it may be impacted in the future as iron and steel products are under consideration. Nevertheless, the DPP's capacity to support innovative business models for enhancing aftermarket sales and service contracts was identified as a significant factor influencing compressor repair operations.

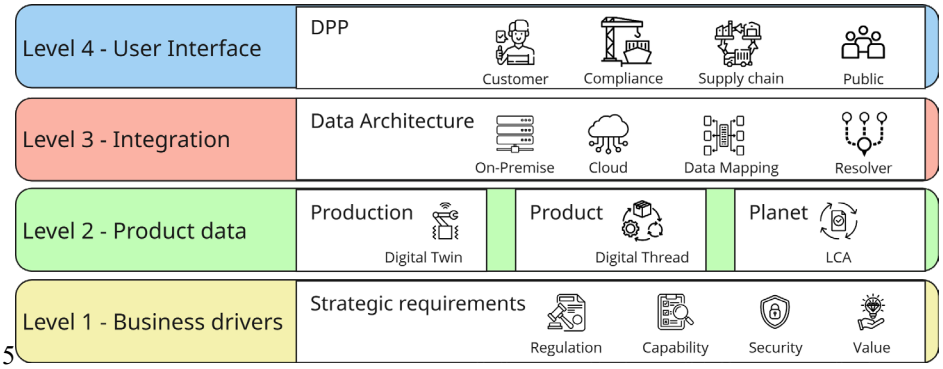

Figure 3 - NMIS ReMake Digital Product Passport Framework

With the requirements of the DPP established, the company would advance to level 2 of the framework (Figure 3) by specifying their product data and begin to evaluate their entire product lifecycle, emphasising remanufacture, repair, reuse, and recycling opportunities. At this stage, an organisation is utilising Industry 4.0 paradigms to begin data capture from various systems. This project employed digital threads for the management of product data utilising Model Based Design & Quality Information Framework (MBD/QIF) [16], production data for carbon emissions through digital twins [17] and review of global product impacts through LCA. Product data at level 2 is assessed on its potential to improve value retention through data sharing, as well as its ability to tackle difficulties in managing the product data in a value chain that lie beyond an organisation's control. Level 2 data within an organisation is typically siloed and stored in separate systems, and to address this, an organisation would move to level 3 of the NMIS ReMake DPP Framework.

At level 3, the framework supports the organisation in evaluating data architectures on data security, the DPP view for different stakeholders, and the interoperability requirements. Access to the data contained within the DPP is available to multiple stakeholders, with differentiation based on the role of the stakeholder (i.e., manufacturer, customer, supply chain) and the type of data involved [13]. Level 3 of the framework utilises a GS1 standard [18] to fulfil this requirement. A fundamental requirement of the DPP is that it should be completely interoperable with other DPPs [13]. To assist organisations in achieving this objective, an open-source Python library [19] was created to facilitate data mapping activity required to bring Level 2 data to end users (Level 4). The Level 3 integration layer evaluates the solution architecture for an organisation for deploying a DPP that meets data security through private cloud and on-premise infrastructure. It maps siloed product data identified in the Level 2 layer with the NMIS ReMake

DPP data model, while fulfilling the ESPR requirement for DPP system interoperability to enable access to relevant product data by key stakeholders. NMIS ReMake DPP data model identifies key data attributes to support remanufacturing processes which include repair identification, material data, resource models and reference to MBD/QIF identifications.

The framework's Level 4 (Figure 3) user interface helps the organisation create the end-user experience of interacting with a DPP. In this project, a customer-focused DPP view was developed as shown in Figure 4a, that strikes a balance between complex product data and end-of-life information to support CE goals. To enable knowledge exchange with principles of open sources, a reference 'NMIS ReMake Product' as shown in Figure 4b, was manufactured and remanufactured to put the NMIS ReMake DPP Framework in practice.

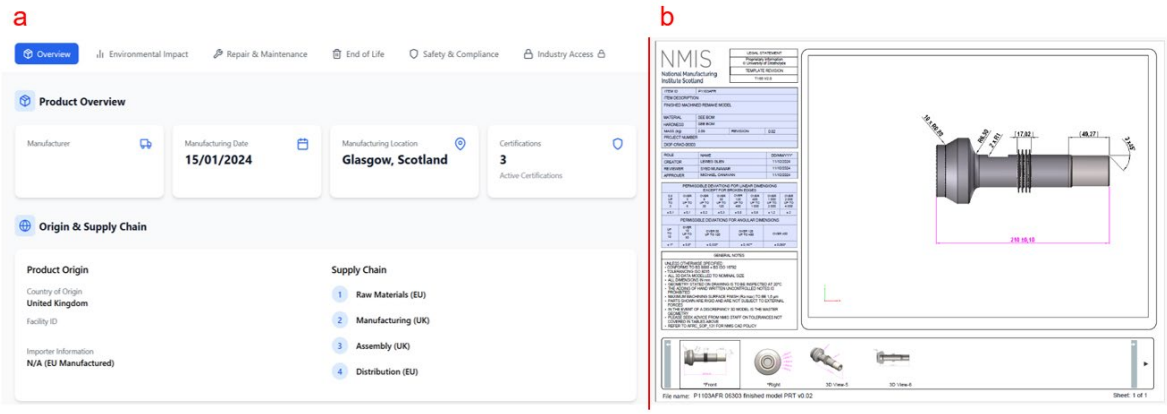

Figure 4 - (a) Customer view of Digital Product Passport, (b) NMIS ReMake Reference Product

Servitisation Business Model

Through parallel implementation of the HPCS and DPP technologies, a fundamental shift in how high-integrity sectors approach product lifecycle management is enabled. By transitioning to a servitisation business model, the life cycle of the part can be completely re-evaluated with the aim of value retention. By retaining ownership of assets and providing ongoing aftermarket services, manufacturers are incentivised to design for durability, reparability, and recyclability. In the context of the compressor case-study investigated in this work, parts are returned for repair activities, such as re-application of the HPCS coating in the high wear areas of the compressor. A complete history of aftermarket care is then logged within the DPP, creating a robust foundation for quality control. This shift from reactive to proactive maintenance reduces unexpected failures, lowering operational costs for customers by an estimated 20% annually, and providing lead time reductions of 80% compared to new manufacture.

The servitisation business model approach aligns profitability with sustainability goals. The predictable revenue streams provided through service contracts for the compressor are beneficial for the manufacturer, as well as the customer, who benefits from paying for uptime rather than large capital expenditure. The implementation of a servitisation business model focused on aligning the manufacturer's profitability with sustainability by transitioning from a product-sales approach to service-based offerings.

The servitisation model for the company was tailored for high-value and mission-critical products through a combination of proactive and semi-proactive service strategies. These strategies leveraged existing support structures, such as maintenance contracts and repair services. To understand the key elements of the customised servitisation model, an evaluation of different CE options, products, and market/customer was conducted. It found that the key elements of the model included life-cycle agreements, where manufacturers retained ownership of components, and "pay-per-use" contracts that aligned customer costs with operational outcomes. The introduction of a pay-per-use model for compressor maintenance reduced upfront capital expenditure for customers by 35%, while securing a stable 10% increase in aftermarket revenue for the manufacturer over a two-year period. This embedded relationship with the end-users created a natural mechanism for remanufacturing, as components can now be tracked, serviced, and refurbished throughout their lifecycle.

Discussion

Achieving value retention and circularity in high-integrity sectors requires a combination of advanced manufacturing techniques, digital tools, and sustainable business models. This project exemplifies the benefits of an interdisciplinary approach, integrating these core technologies to address the systemic challenges of adopting circular economy practices. Unlike previous studies that have explored these components in isolation, this research presents an integrated framework where DPPs facilitate traceability in additive manufacturing repair processes, and servitisation ensures long-term economic viability by aligning company incentives with sustainability goals.

Advanced manufacturing techniques provide the physical foundation for remanufacturing and repair by enabling the development of alternative coatings and processes to replace legacy solutions like EHC. These technologies not only improve the performance and lifespan of components but also align with circularity goals by facilitating repair, reuse, and remanufacture. The Digital Product Passport ensures traceability, compliance, and lifecycle management for remanufactured components. By creating a digital record of a product's history, from manufacture to repair and reuse, the DPP enables transparency across supply chains, supports the implementation of EU circular economy regulations, and opens new avenues for monetising the aftermarket. In contrast of conventional DPPs, the NMIS ReMake DPP incorporates key remanufacturing attributes, such as repair history, coating thickness validation, deposition quality metrics, and lifecycle failure predictions. These features enable more precise service scheduling, reducing downtime and improving the overall reliability of remanufactured components. Meanwhile, servitisation business models incentivise circularity by shifting the traditional product ownership model toward service-based contracts. This approach encourages manufacturers to design for durability, reparability, and recyclability while providing customers with predictable service costs and reduced capital expenditure. This study demonstrates how servitisation, combined with DPP tracking, enables companies to transition from a high-material-cost business model to a value-retention strategy where revenue is derived from long-term service agreements rather than component replacements. By integrating predictive maintenance insights within the DPP, manufacturers can anticipate failures, schedule proactive interventions, and optimise inventory management, further reducing operating costs.

The integration of advanced manufacturing techniques and the DPP further enhanced the developed servitisation model. These technologies enabled cost-effective remanufacturing processes for worn components, ensuring consistent performance and reducing downtime for customers. HPCS was selected due to its ability to deposit dense coatings with high adhesion strength, making it a viable alternative to EHC. By integrating the DPP into this process, real-time coating quality data, material usage, and failure rates can be captured, enabling data-driven remanufacturing strategies. This ensures that each remanufactured component is validated for continued service, addressing certification and compliance concerns in high-integrity sectors. The DPP added further value by capturing and managing lifecycle data, allowing manufacturers to optimise service schedules, track maintenance history, and gain a deeper understanding of component failures. For the case study, this approach reduced reliance on intermediaries, improved reverse logistics, and strengthened customer trust. Together, these outcomes demonstrate a scalable framework for integrating remanufacturing into service-based models and highlight how technology-driven solutions can deliver operational and financial benefits. While the presented study focuses on high-integrity sectors, the framework is adaptable to other industries where remanufacturing is underutilised. By leveraging digital tracking and advanced repair methodologies, this approach can accelerate circular economy adoption across diverse manufacturing domains, supporting global sustainability objectives.

This interdisciplinary framework, which unites physical innovation, digital infrastructure, and economic incentives, underscores the importance of addressing circular economy adoption as a systems-level challenge rather than a series of isolated technological fixes. Its scalability and adaptability make it particularly relevant for other high-integrity industries. For instance, in renewables, extending the lifespan of offshore wind components, such as turbines and transmission systems, could significantly reduce costs and emissions. By leveraging tools like the DPP to track material usage and lifecycle data, manufacturers can improve operational efficiency, turbine up-time and compliance with sustainability targets. In aerospace, leveraging value-retention provided by this framework offers significant benefits. Reducing the demand on overburdened and complex supply chains helps to address long lead times while maximising the resource efficiency of high-performance and high-cost materials. This approach can enhance resilience in a sector that relies heavily on material availability and precision manufacturing.

The journey to integrating these disciplines also revealed several unexpected secondary benefits. For example, increased repairs have reduced the need for new compressor products to be fully manufactured, creating a more streamlined shopfloor workflow. Additionally, focusing on remanufacturing has allowed the compressor company to

invest in innovative technology with a clear return on investment, enhancing its resilience in competitive markets. These outcomes highlight how a unified approach can deliver value beyond the initial scope of its objectives.

By capturing lifecycle data through the DPP and linking it to servitisation business models, this approach also enhances manufacturers' understanding of component failure modes and degradation mechanisms. This knowledge can drive further design improvements, enabling continuous innovation and reinforcing the economic case for circular practices.

This work demonstrates how an interdisciplinary approach, with its ability to deliver both anticipated and unforeseen benefits, can create a robust foundation for accelerating circularity and value retention across sectors. Its adaptability and scalability hold promise for broader industrial applications, advancing the global transition towards a circular economy.

Conclusions & Recommendations

This work demonstrated that achieving circularity in high-integrity sectors requires an interdisciplinary framework integrating advanced manufacturing, digital tools, and circular business models. The insights gained from the ReMake Glasgow and Remake Value Retention Centre projects highlight practical pathways to accelerate value retention practices and provide scalable solutions for broader sectoral and regional adoption.

Key Conclusions:

- The interdisciplinary framework demonstrated in this project has significant potential to scale across other sectors. Although this work focused on energy compressors, the same approach could be applied to renewables, consumer goods, aerospace and other industries. By building on these insights, businesses can replicate solutions that reduce emissions, save costs, and drive economic growth across supply chains.
- Achieving circularity in high-integrity sectors like aerospace, wind energy, and power generation requires more than technological innovation alone. This work shows that integrating advanced manufacturing techniques, Digital Product Passports (DPPs), and servitisation business models can overcome technical, digital, and economic challenges, accelerating the adoption of value retention practices in ways that isolated solutions cannot achieve.
- Advanced manufacturing techniques open up new possibilities for remanufacturing. The methods highlighted in this study, including Additive Manufacturing, demonstrated improvements in wear resistance, fatigue life, and cost reduction. These results show the potential of these technologies to replace legacy solutions, extend product lifespans, and reduce environmental impact.
- Digital Product Passports provide critical transparency, traceability, and lifecycle management. By capturing data such as manufacturing quality, service history, and material usage, the DPP facilitates compliance with EU legislation, improves supply chain efficiency, and supports informed decision-making for both manufacturers and customers.
- Servitisation business models create strong incentives for durability and value retention. Shifting from product sales to service-based contracts aligns profitability with circular economy goals. Retaining ownership of components and offering flexible service agreements encourages manufacturers to prioritise durability, reparability, and lifecycle optimisation, reducing waste while opening up new revenue streams.

Recommendations:

- The Digital Product Passport developed in this project should be applied to other sectors with strong potential for circularity, such as offshore wind, heavy manufacturing, and other high-value industries. By establishing open standards and ensuring interoperability, DPPs can streamline lifecycle management, improve adoption, and help industries meet EU sustainability targets.

- The servitisation model outlined in this work should be refined and trialled in other industries. Adapting the model to specific customer needs and regulatory requirements will encourage wider use and demonstrate its ability to balance profitability with sustainability.
- Industry-specific roadmaps are needed to guide sectors in adopting circular economy practices. These should include clear steps for integrating advanced manufacturing, DPPs, and servitisation models while addressing common barriers such as outdated systems and regulatory challenges.
- Wider adoption of advanced manufacturing techniques, including High-Pressure Cold Spray and Laser Cladding, should be encouraged across industries where applicable. These technologies offer cost-effective ways to repair and remanufacture components, improve material performance, and extend product lifecycles. Coupling these innovations with DPPs will further accelerate progress towards a circular economy.

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About the Authors

Stephen Fitzpatrick - University of Strathclyde (National Manufacturing Institute Scotland): Stephen is Director at the National Manufacturing Institute Scotland, University of Strathclyde, and Director of the £10m Remake Value Retention Centre. His work focuses on circular economy solutions for high-integrity sectors.

Dr Andreas Reimer - University of Strathclyde (National Manufacturing Institute Scotland): Andreas is the theme lead for ReMake at the National Manufacturing Institute Scotland and he leads the ReMake Glasgow project. His expertise lies in developing net zero processes and adv. manufacturing processes.

Dr Calum Hicks - University of Strathclyde (National Manufacturing Institute Scotland): As technical lead on High-Pressure Cold Spray technology and with broad expertise in Direct Energy Deposition additive manufacturing, Calum works to facilitate their adoption across the high-value manufacturing industries by developing and validating novel solutions to industrial challenges.

Syed Munawar - University of Strathclyde (National Manufacturing Institute Scotland): Syed leads the Virtual Manufacturing group at NMIS and developed and led Digital product Passport work, creating the first DPP for remanufacturing.