UNIVERSITY OF OXFORD

DIGITAL ENABLERS FOR REMANUFACTURING

A STATE-OF-THE-ART REVIEW AND GAP ANALYSIS OF DIGITAL TECHNOLOGIES IN CIRCULAR PRODUCTION SYSTEMS

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FORWARD

Remanufacturing is increasingly recognised as a strategic pillar of Europe's industrial transition. It preserves embedded value, reduces resource dependency and strengthens resilience in the face of supply volatility and geopolitical uncertainty. Yet despite its promise, remanufacturing remains constrained by variability, fragmented information flows and limited system integration.

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Digital technologies are advancing rapidly across manufacturing. Their application to remanufacturing, however, requires a different systems logic—one that can manage uncertainty, integrate product history across actors and support trust in circular value chains.

The purpose of this study is to examine how digital technologies are currently applied in remanufacturing, where integration gaps persist and where future innovation should concentrate. It aims to inform researchers, industry leaders and policymakers working to position remanufacturing as a mainstream industrial capability.

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KEY CONCEPTS

Remanufacturing	An industrial process that restores a used product to as-new functional performance, typically including disassembly, inspection, component restoration or replacement, reassembly and testing, often supported by warranty equivalence.
Structural Uncertainty	Intrinsic variability in product condition, return timing and information availability that characterises remanufacturing systems and complicates planning and execution.
Product-Centric Architecture	A digital system design in which the product, rather than the process, serves as the organising principle linking identity, sensing, analytics and execution across the lifecycle.
Integration Readiness	The degree to which digital technologies are connected end-to-end across systems, actors and lifecycle stages rather than deployed as isolated tools.
End-to-End Integration	Continuous connectivity of product identity, data and decision-making from intake through restoration to redeployment.
Triple Bottom Line	A performance framework assessing economic, environmental and social impact.

GLOSSARY

AI	Artificial Intelligence
AR	Augmented Reality
CLD	Causal Loop Diagram
CORDIS	Community Research and Development Information Service
DPP	Digital Product Passport
EIC	European Innovation Council
ERP	Enterprise Resource Planning
EU	European Union
IoT	Internet of Things
MES	Manufacturing Execution System
ML	Machine Learning
MR	Mixed Reality
PLM	Product Lifecycle Management
RFID	Radio Frequency Identification
TRL	Technology Readiness Level
VR	Virtual Reality

EXECUTIVE SUMMARY

Remanufacturing has the potential to preserve embedded industrial value, reduce resource dependency and strengthen European resilience. Yet despite decades of discussion and technological advancement, remanufacturing remains constrained by structural uncertainty. Upstream uncertainties cascade through operations, increasing process variability and weakening the business case for scale.

Digital technologies, including the Internet of things (IoT) and smart factory system, are frequently presented as the remedy. Most of these technologies are mature and widely deployed in conventional manufacturing. However, this study finds that in remanufacturing, these technologies are typically applied in isolation. Integration remains limited. As a result, digital progress has strengthened individual components but not yet transformed the system.

Key Findings

Four structural barriers dominate the literature: unpredictable product quality, weak business case, data gaps and unstable return flows

- Roughly 70% of technology–barrier links in academic studies remain conceptual rather than demonstrated
- Digital technologies in remanufacturing are fragmented and rarely connected end-to-end
- Enterprise integration layers (ERP, PLM, lifecycle systems) are largely absent from most innovation projects
- Automation improves productivity but does not resolve upstream uncertainty
- Workforce capability and data availability emerge as central leverage points in the system
- Horizon innovation activity remains weighted towards downstream efficiency and recycling rather than upstream uncertainty reduction
- The primary constraint is integration readiness, not technological scarcity

The next phase of digital remanufacturing is not about inventing new technologies. It is about system design. To unlock scale, digital tools must be integrated around the product as the organising principle, connecting identity, sensing, analytics, execution and lifecycle governance across actors. Without this shift from process optimisation view to product centric workflow, remanufacturing will remain characterised by pilots and local optimisation rather than becoming a resilient, mainstream industrial strategy.

"SCALING REMANUFACTURING REQUIRES A SHIFT FROM PROCESS-CENTRIC OPTIMISATION TO INTEGRATED, PRODUCT-CENTRIC SYSTEMS BUILT TO MANAGE VARIABILITY AND UNCERTAINTY."

REMANUFACTURING IN AN AGE OF UNCERTAINTY

REMANUFACTURING OFFERS SIGNIFICANT POTENTIAL FOR RESILIENCE AND VALUE RECOVERY, YET IT REMAINS CONSTRAINED BY VARIABILITY, FRAGMENTED INFORMATION FLOWS AND CONTINUED RELIANCE ON MANUAL EXPERTISE.

Remanufacturing is an industrial process that returns a used product, often called a core, to an as-new condition through a structured sequence of disassembly, cleaning, inspection, restoration or replacement of components, reassembly, and final testing. In most definitions, remanufacturing also implies performance that is at least equivalent to a new product, and it is often supported by a warranty that provides confidence in quality. A study commissioned by the European Remanufacturing Council has argued that the economic potential of remanufacturing in Europe is substantial. In a high-adoption scenario, the study estimates that remanufacturing could approach a production value of around €100 billion by 2030, while also highlighting that a major scale-up of remanufacturing could support more than half a million jobs.

Remanufacturing is being adopted across a range of industries and is particularly compelling in two contexts. The first is where individual components retain substantial remaining useful life even when the product is retired. In these cases, remanufacturing can recover embedded value that would otherwise be lost through early end-of-life processing. The second is where products face functional or technological obsolescence. While refurbishment can extend product life through targeted repair and cosmetic improvement, remanufacturing is more thorough, and it can therefore support a deeper restoration of functionality by allowing upgrades to be incorporated as part of the rebuilding process. This higher effort can be justified when it delivers a substantial increase in usable life and reliability, rather than a modest extension.

The literature highlights environmental performance and supply chain resilience as key drivers behind growing interest in remanufacturing. It is considered a higher-value circular strategy than recycling because it preserves more of the embedded value within products and components. As markets for both virgin and recycled materials become increasingly volatile and competitive, remanufacturing can reduce reliance on primary inputs by avoiding the repetition of upstream processing that is already embodied in returned components.

However, remanufacturing remains a manual and skill-intensive process. While conventional manufacturing is increasingly shaped by Industry 4.0, with connected devices, integrated enterprise systems, and cloud-enabled architectures supporting standardised and repeatable production, remanufacturing continues to rely heavily on tacit knowledge and operator judgement. This is largely because it must cope with high variability at every stage. Product condition differs case-by-case; disassembly paths are uncertain, and component quality is difficult to determine. As a result, decision-making is often situational and difficult to codify. This contrast creates a clear tension. On the one hand, remanufacturing is positioned as a high-value circular strategy with substantial economic and environmental promise. On the other, its operational foundations remain labour-intensive and fragmented, limiting scalability and consistency. If remanufacturing is to expand in line with its projected potential, its processes must become more transparent, predictable, and systematically managed without losing the flexibility required to handle variability.

It is in this context that digital technologies become relevant. The question is not whether remanufacturing is important, but whether existing and emerging digital tools can address its specific operational challenges. This paper therefore examines the state of the art in digital technology applications for remanufacturing, drawing on both academic research and European innovation activity. It synthesises evidence to answer five research questions that clarify which digital technologies are being applied, how they are combined within remanufacturing systems, and which barriers and enablers shape technology adoption in practice.

EVIDENCE-BASED ANALYSIS ACROSS RESEARCH AND PRACTICE

THIS STUDY COMBINES SYSTEMATIC ACADEMIC EVIDENCE AND REAL-WORLD INNOVATION ACTIVITY TO EXAMINE NOT ONLY WHICH TECHNOLOGIES ARE PROPOSED FOR REMANUFACTURING, BUT WHERE INTEGRATION GAPS PERSIST IN PRACTICE.

The research combines an academic synthesis and an innovation portfolio scan to establish the state of the art in digital technology applications for remanufacturing, and to identify where research and innovation are—or are not—addressing the constraints that matter most in practice. The academic evidence base was built through an initial Scopus search focused on digital technologies applied to remanufacturing, followed by forward and backward snowballing to broaden coverage and strengthen the evidence base on remanufacturing barriers, resulting in a corpus of approximately 55 peer-reviewed studies. These studies were qualitatively coded using MAXQDA, a mixed-methods data analysis software, to identify the key barriers and technology adoption levels.

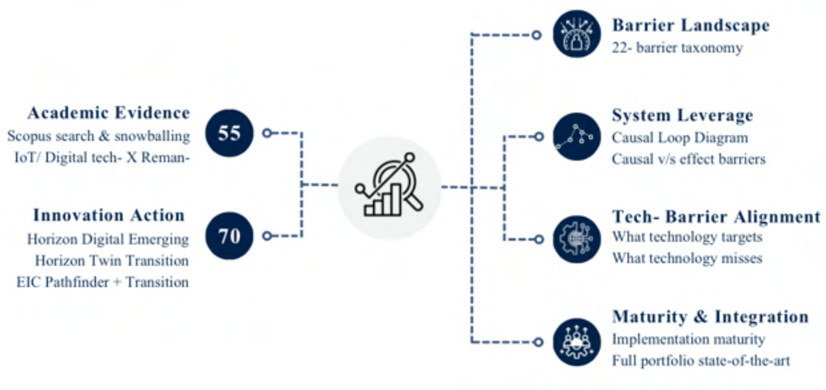


Figure 1. This figure summarises how the report was developed, combining two evidence streams—peer-reviewed academic literature on digital technologies applied in remanufacturing and a CORDIS-based scan of European Horizon and EIC innovation projects. The combined qualitative evidence was coded to identify 22 barrier categories and assess technology application and maturity.

The barrier framework developed as a result was used to construct a causal loop diagram to understand the system's view and highlight the interactions between barriers and their downstream effects. This view is used to identify root causes and leverage points and is also used to understand whether technology is applied to solve the fundamental problems in the system.

To complement the academic perspective with an implementation-oriented view of where technology development is actively being pursued, the study also analysed European research and innovation activity using the CORDIS platform. The analysis focused on Horizon Europe calls that emphasise digital innovation and industrial application (Digital and Emerging, and Twin Transition), as well as EIC instruments under the Pathfinder and Transition programmes. The data were analysed quantitatively to reveal where innovation efforts concentrate and where gaps remain for future collaborative action.

UNCERTAINTY DRIVES REMANUFACTURING'S CONSTRAINTS

ACROSS A DECADE OF RESEARCH, THE SAME FOUR BARRIERS DOMINATE REMANUFACTURING DISCOURSE. AT THE CORE OF THE PROBLEM SITS AN INFORMATION VOID THAT UNDERMINES PLANNING, COORDINATION, AND CONDITIONS NEEDED FOR SCALE.

Across the coded corpus (55 papers, 2017–2025; 472 barrier-evidence segments across 22 barriers), the literature converges on a consistent diagnosis: remanufacturing is constrained less by a single technical bottleneck and more by a tightly coupled set of uncertainties and operational frictions that make planning, execution, and investment difficult.

The "Big Four" structural constraints stand out because they combine high segment counts with wide coverage across studies and persistence across multiple years :

- Unpredictable product quality (54 segments; 34 papers)
  Returned products vary widely in condition, which drives uncertainty in disassembly effort, inspection outcomes, component recovery rates, and final quality performance.
- Poor business case (52 segments; 24 papers)
  Economic viability is repeatedly cited as a barrier, but the way it is discussed suggests it often functions as an outcome barrier created by uncertainty, variability, and weak information flows rather than a single root cause.
- Information access / data barriers (47 segments; 28 papers)
  Lack of product history, condition data, traceability, and missing data-sharing arrangements limits decision quality and hinders inspection effort, slowing triage, and undermining coordination.

- Unstable return quantity and timing (40 segments; 28 papers)
  Unpredictable core inflows weaken capacity planning and increase unit cost, making it harder to design stable remanufacturing operations.

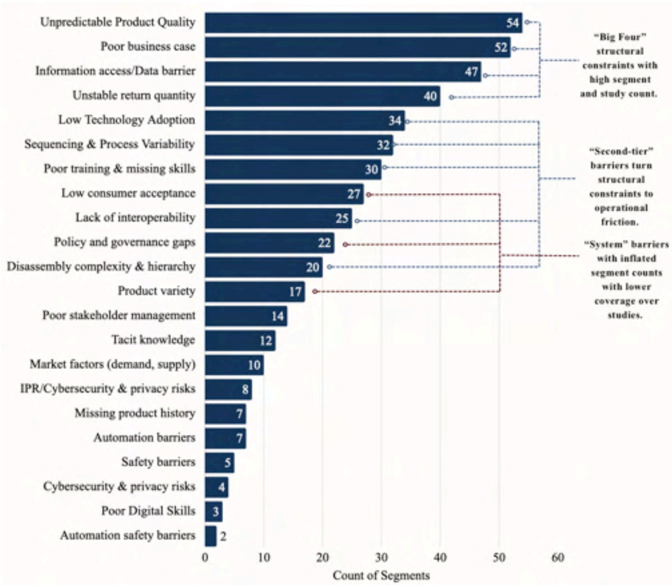


Figure 2. The chart ranks the 22 barrier categories by the number of coded evidence segments (n = 472) identified across 55 peer-reviewed remanufacturing studies (2017–2025). Segment frequency reflects the intensity with which barriers are discussed, not their standalone severity.To avoid over-interpreting raw frequencies, segment totals were considered alongside paper-level prevalence, distinguishing widely recognised structural constraints from barriers discussed in depth within a smaller subset of publications. The distribution highlights four dominant barriers—unpredictable product quality, weak business case, information and data gaps, and unstable return quantity—suggesting that remanufacturing challenges are rooted in systemic uncertainty and information asymmetry rather than isolated technical shortcomings. The figure provides the empirical foundation for the subsequent causal loop analysis, which examines how these barriers interact and reinforce one another.

SECOND-TIER BARRIERS TURN UNCERTAINTY INTO OPERATIONAL FRICTION

Beyond the Big Four, the literature repeatedly points to a second tier of barriers that explain why uncertainty becomes expensive and difficult to manage on the shopfloor.

- Low technology adoption (34 segments; 21 papers) and skills/training gaps (30 segments; 21 papers) are cited as practical constraints on implementing decision support and digitization—particularly where outcomes depend heavily on manual judgement and tacit expertise.
- Sequencing and process variability (32 segments; 19 papers) reflects the operational reality that workflows cannot be easily standardised when product condition and required steps vary case by case.
- Poor training and missing skills (30 segments; 21 papers) is a key capability barrier that reflects the difficulty of sustaining remanufacturing operations when specialised technical knowledge. Inspection expertise and process know-how are limited, particularly in contexts where variability and uncertainty demand higher levels of workforce judgement and adaptability.
- Lack of interoperability (25 segments; 17 papers) is another challenge since even when data is available, it cannot always be read, understood or used as systems are not always in place for stakeholders to exchange information reliably across the reverse chain.
- Finally, disassembly complexity (20 segments; 14 papers) remains a recurring bottleneck, driven by product design diversity and the need to decide how far to disassemble under uncertain condition and value recovery.

Some barriers, such as low consumer acceptance (27 segments; 12 papers), policy and governance gaps (22 segments; 9 papers) and product variety (17 segments across 8 papers) look inflated by segment counts but have narrower coverage over papers. While these are legitimate barriers to remanufacturing, segment-based ranks alone may overstate the breadth, and therefore, paper level prevalence is taken into consideration in identifying tier 1 and tier 2 barriers that dominate.

SYSTEM DYNAMICS OF REINFORCING CONSTRAINTS

THE CAUSAL LOOP ANALYSIS SHOWS THAT REMANUFACTURING CHALLENGES ARE NOT ISOLATED BOTTLENECKS BUT MUTUALLY REINFORCING DYNAMICS. DATA GAPS AMPLIFY QUALITY UNCERTAINTY, WHICH INCREASES PROCESS VARIABILITY AND WEAKENS ECONOMIC VIABILITY, LIMITING INVESTMENT IN SKILLS AND SYSTEMS. AUTOMATION ALONE CANNOT BREAK THESE LOOPS. THE STRONGEST LEVERAGE POINTS LIE IN DATA CONTINUITY AND WORKFORCE CAPABILITY AND NOT IN PRODUCTIVITY GAINS ALONE.

A causal loop diagram is a visual tool that maps cause-and-effect relationships among variables in a system. By illustrating how factors influence one another and form feedback loops, a CLD helps reveal complex interdependencies that might be missed in a linear analysis of barrier counts. Since the 22 barriers identified through qualitative analysis are highly interconnected, examining their dynamics as a whole system rather than in isolation was crucial to understanding how they reinforce one another.

The causal loop diagram reveals eight reinforcing dynamics that explain how remanufacturing systems either stabilise and improve or become trapped in persistent inefficiency.

- R1 – Capability investment loop: Economic viability enables investment in technology adoption. Greater technology adoption reduces process variability (simulation tools, digital twins, smart factories) and improves operational stability, which in turn strengthens economic viability.
- R2 – Data uncertainty reinforcement loop: Technology adoption (product identification systems, PLM solutions, service platforms) improves data availability, which reduces product quality and return uncertainty. Lower uncertainty stabilises processes and strengthens economic viability, allowing further investment in technology.
- R3 – Data trust acceptance loop: Improved data availability increases transparency and credibility (digital product passports, product twins, lifecycle impact reporting), which strengthens consumer acceptance. Stronger acceptance supports market demand and economic viability, reinforcing the system's ability to invest in technology and data infrastructure.
- R4 – Workforce capability loop: Higher workforce skill adequacy reduces product quality uncertainty and process variability. Improved stability enhances economic viability, enabling further investment in skills.

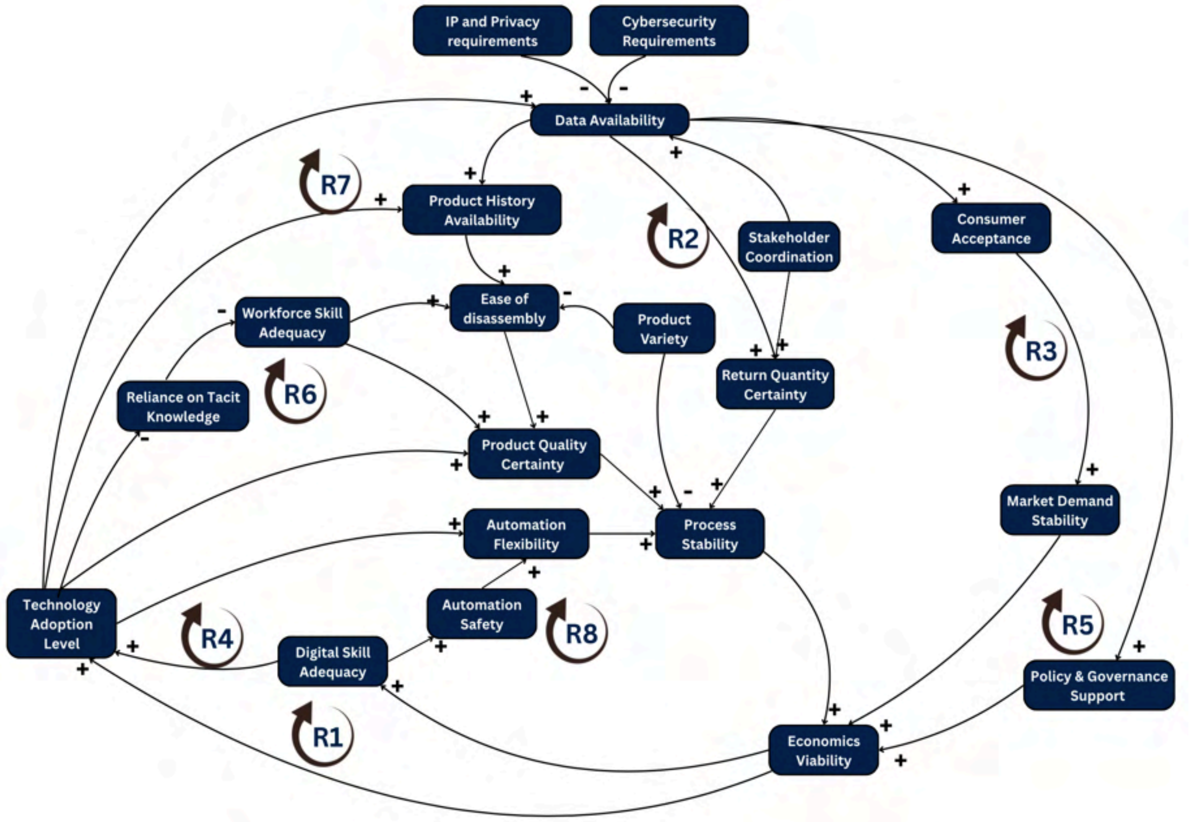


Figure 3. The CLD maps 22 evidence-derived barriers into eight reinforcing feedback loops (R1–R8). Three core system dynamics are highlighted: human-centric capabilities and tacit knowledge (grey), data infrastructure and traceability (yellow), and automation and digital tools (blue). The structure emphasizes that while automation (R8) plays a role, the most influential feedback emerges from quality uncertainty, workforce skills, and data gaps (R2, R4, R6, R7). These leverage points reinforce each other and reveal where systemic intervention is most impactful — independent of technology-focused efforts currently dominating the literature

- R5 – Policy–data reinforcement loop: Supportive policy (standardisation) encourages technology adoption and strengthens data infrastructures. Better data improves monitoring, standard setting, and consumer confidence, which enhances economic performance and reinforces the policy environment.
- R6 – Capability scaling loop: Reliance on tacit knowledge limits the distribution of skills across the workforce, reducing the ability to make decisions under quality uncertainty and variability. This weakens economic viability and constrains investment in training and upskilling activities.
- R7 – Disassembly performance loop: Product variety, limited product history, and missing worker skills increase disassembly complexity and amplify quality uncertainty and process variability, reducing economic viability. This limits the system's ability to invest in better information and capability.

- R8 – Automation reinforcement loop: Digital skill adequacy supports safe and flexible automation (cobots, automation, adaptive manufacturing), which improves productivity despite residual process variability and strengthens economic viability, allowing further investment in digital capability. However, this loop remains largely confined to operational performance and does not address upstream uncertainty.

The most powerful leverage points are the variables from which the largest number of causal links originate. Data availability constraints emerge as a central driver, influencing quality uncertainty, return uncertainty, consumer trust, and policy effectiveness. Workforce skill adequacy is another critical leverage point, shaping disassembly complexity, quality assessment, and the system's dependence on tacit knowledge. Although technology adoption is highly connected, it is largely an outcome of other conditions and cannot be influenced directly at the outset.

DIGITAL TOOLS ADDRESS THE RIGHT BARRIERS, BUT ONLY PARTIALLY

DIGITAL TECHNOLOGIES ARE FREQUENTLY APPLIED TO INFORMATION ACCESS, SKILLS SHORTAGES AND PROCESS VARIABILITY, AREAS THAT CORRESPOND TO THE IDENTIFIED LEVERAGE POINTS. HOWEVER, MOST APPLICATIONS REMAIN CONCEPTUAL OR CONFINED TO LOCAL IMPLEMENTATION. DATA-CENTRIC TOOLS DOMINATE THE DISCUSSION, WHILE ENTERPRISE INTEGRATION AND LIFECYCLE CONTINUITY REMAIN UNDERDEVELOPED. AS A RESULT, DIGITAL INTERVENTIONS IMPROVE ISOLATED PARTS OF THE SYSTEM WITHOUT MATERIALLY REDUCING STRUCTURAL UNCERTAINTY.

Data and information access is the barrier most often linked to digital solutions in the literature. In the coded evidence, this barrier is addressed in roughly 50 segments. Many papers describe how poor product data, weak traceability, and limited information flow could be improved through tools such as sensors, digital twins, product passports, and analytics. The digital skills gap is also prominent. It appears roughly 45 times, and many authors argue that technologies such as augmented reality training, operator guidance, and knowledge-sharing platforms can help organisations that struggle to find, train, or retain skilled workers in remanufacturing. Other frequently addressed barriers include process efficiency and cost, and systems integration, where robotics, optimisation tools, connected devices, and cloud platforms are presented as ways to reduce cycle times, improve productivity, and overcome siloed systems and weak interoperability. These themes recur because authors often make an explicit link between a barrier and a proposed digital intervention.

The evidence also shows a clear difference between what the literature suggests is possible and what has been demonstrated in practice. Of the roughly 50 coded segments that address data and information access, about 15 describe case demonstrations, such as sensors or digital twins being used to provide product condition data in a remanufacturing case study. The remaining ~35 segments describe data access as a potential solution rather than a proven one. A similar pattern is visible for workforce skills. Although the skills gap appears roughly 45 times, only about one third of these instances describe real implementation, such as studies in which augmented reality was used to guide workers successfully, while the remainder are conceptual proposals. Process efficiency barriers and integration barriers are also discussed in dozens of segments, with technologies such as robotics, optimisation algorithms, and enterprise platforms frequently cited as remedies. By contrast, less frequent barriers, such as regulatory issues and customer acceptance, appear in under 20 segments and tend to be discussed mainly in theory, with very few concrete examples.

Overall, the topics most frequently addressed by technology align well with the leverage areas suggested by the barrier analysis. The prominence of data and information access, at roughly 50 segments, reinforces the view that information is a critical missing link in remanufacturing. Many proposed solutions aim to create richer and more reliable information about product history, condition, and process performance. The attention given to the digital skills gap, at roughly 45 segments, also reflects a consistent belief that human capability is essential, particularly in a sector that still depends on judgement and experience at many points in the process. This alignment suggests that researchers are directing digital interventions towards barriers where better data and stronger operator capability could have a transformative effect. At the same time, some potential leverage areas receive less attention in the digital solutions discourse, especially those that sit outside the factory, such as organisational change and policy support.

A key insight is the imbalance between conceptual proposals and real-world demonstrations. In the coded data, roughly 70 per cent of the technology-to-barrier links are conceptual and framed as potential solutions, while only about 30 per cent involve demonstrated solutions, such as a documented pilot implementation. This approximate 2:1 ratio shows that much of the academic discourse remains forward-looking. Many publications propose that improved data infrastructures, digital twins, or augmented reality training could overcome information gaps or skill shortages, yet fewer studies report implementations that achieve sustained operational outcomes.

The distribution across barriers reinforces this observation. Information-related barriers, such as data access and missing product history, are addressed using sensors, RFID, digital twins, blockchain, and enterprise systems. These barriers attract the highest volume of technological attention, including several standalone novel technologies clustered here under “Other IoT/other”, but implementation maturity remains uneven. In contrast, physically embedded challenges, such as disassembly complexity, show stronger links to robotics, machine vision, and human–robot collaboration, with comparatively stronger evidence of industrial experimentation. This suggests that while data-centric solutions dominate the conceptual landscape, embodied process technologies are closer to operational deployment.

Simulation and modelling technologies are particularly prominent in relation to poor business case and sequencing and process variability. Many studies use simulation to reduce uncertainty, explore flexible process configurations, and estimate cost efficiency under variable return conditions. Robotics and automation are frequently applied to increase throughput and improve productivity, thereby strengthening the economic case for remanufacturing. However, this pattern requires careful interpretation. From a systems perspective, as illustrated by the causal loop structure, automation improves the business case only if low productivity is the true bottleneck.

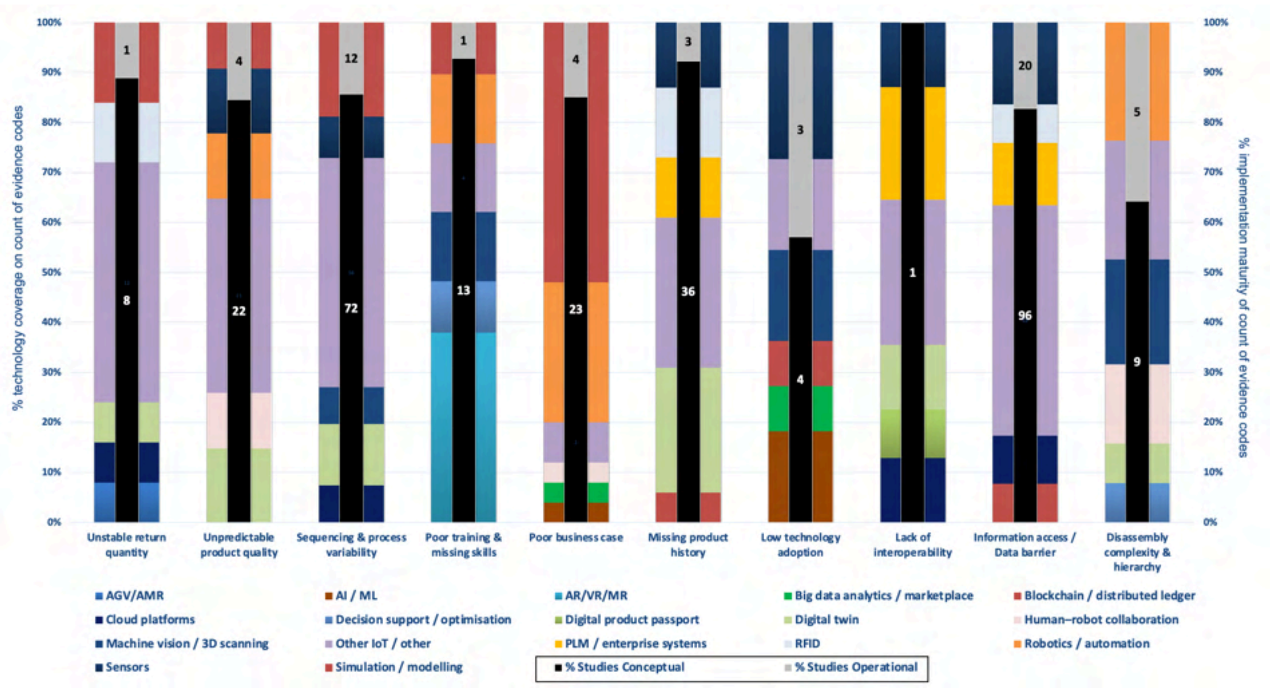


Figure 4. Stacked bars show the five most frequently cited technologies addressing each barrier in the 55-paper corpus, with technologies mentioned fewer than twice grouped as "Other IoT/other". The primary axis represents thick coloured stacks corresponding to technology evidence counts, while the central grey–black narrow stacks on the secondary axis indicates implementation maturity (conceptual versus demonstrated). The figure highlights the dominance of data-centric solutions for information barriers, the prominence of simulation for variability and business case challenges, and the comparatively stronger deployment of robotics and vision technologies in disassembly-related contexts.

If constraints lie earlier in the system, such as unstable return flows and missing product information, additional automation may not resolve the underlying constraint. Instead, it may increase capital investment and financial risk, potentially weakening the business case. This systemic effect becomes visible when analysing the collective evidence across studies but is less apparent in individual publications that focus only on productivity gains.

These patterns should be interpreted carefully, as the analysis reflects literature coverage and does not necessarily represent industry priorities or the success rate of solutions in practice. There is also likely a publication bias towards technologies that are currently prominent and measurable, such as IoT, data analytics, and augmented reality, and towards the barriers they address, especially data availability and skills. Conversely, barriers that are harder to quantify, such as cultural resistance and long-term organisational change, may be under-represented. Finally, a high frequency of a technology and barrier pairing does not guarantee that it is the most critical issue in industry, and a barrier being addressed in theory does not mean it has been solved in practice. For these reasons, the trends reported in this section are best read as an indication of current research focus, rather than as a definitive ranking of urgency or readiness in the field.

MATURE TECHNOLOGIES SUFFER LIMITED SYSTEM INTEGRATION

MOST DIGITAL TECHNOLOGIES APPLIED IN REMANUFACTURING ARE ALREADY MATURE WITHIN CONVENTIONAL MANUFACTURING CONTEXTS. SMART SENSORS, SIMULATION, ARTIFICIAL INTELLIGENCE, ROBOTICS AND ENTERPRISE SYSTEMS OPERATE AT HIGH LEVELS OF READINESS. YET THEIR APPLICATION IN REMANUFACTURING REMAINS LARGELY CONFINED TO PROTOTYPES AND PROCESS-LEVEL IMPROVEMENTS. END-TO-END INTEGRATION ACROSS IDENTITY, SENSING, ANALYTICS AND EXECUTION IS UNCOMMON. THE CONSTRAINT IS NOT TECHNOLOGICAL READINESS, BUT ARCHITECTURAL ALIGNMENT.

We now examine "how" digital technologies are applied in remanufacturing across the academic literature. To enable a structured analysis, all technologies identified in the papers were grouped into five functional categories. Technologies were coded verbatim as described in each study. For example, machine vision systems were coded separately from standalone sensors, and co-occurrence links reflect only integrations that were explicitly reported in the paper. Together, these categories represent the digital building blocks required for an effective remanufacturing system.

1. Item-level digital identity: This category includes technologies such as QR codes and RFID that allow individual products or components to be uniquely identified, making it possible to link physical items to digital records and to track them across different stages of the remanufacturing process.
2. Sensing and connectivity: This category covers sensors, data acquisition systems, and industrial connectivity that help capture data about product condition, process performance, and location, and enable data to flow from the physical system into digital environments.
3. Modelling and analytics: This category includes technologies such as simulation, optimisation, machine learning, and digital twins that analyse data and support decisions such as inspection outcomes, process routing, and resource planning.
4. Digital operation and execution: This category includes robotics, automated machining, and operator support technologies such as augmented or mixed reality that act directly on the physical process by executing decisions or guiding human operators.
5. Lifecycle and data platforms: This category includes enterprise and lifecycle systems such as ERP, MES, PLM, cloud platforms, and digital threads that store, integrate, and govern data across organisational functions and over the product lifecycle.

In principle, a robust remanufacturing solution should combine all five categories. Products should be identifiable; their condition and processing should be sensed; the resulting data should support decisions; and decisions should be executed through machines or guided operators. Information should be stored and shared across the organisation through integrated platforms. However, this ideal configuration was rarely observed in the literature. Excluding review and conceptual papers, only a very small number of studies demonstrated solutions that combined all five categories within a single system. The co-occurrence network in Figure 5 visualises how these technology categories are connected within the analysed corpus.

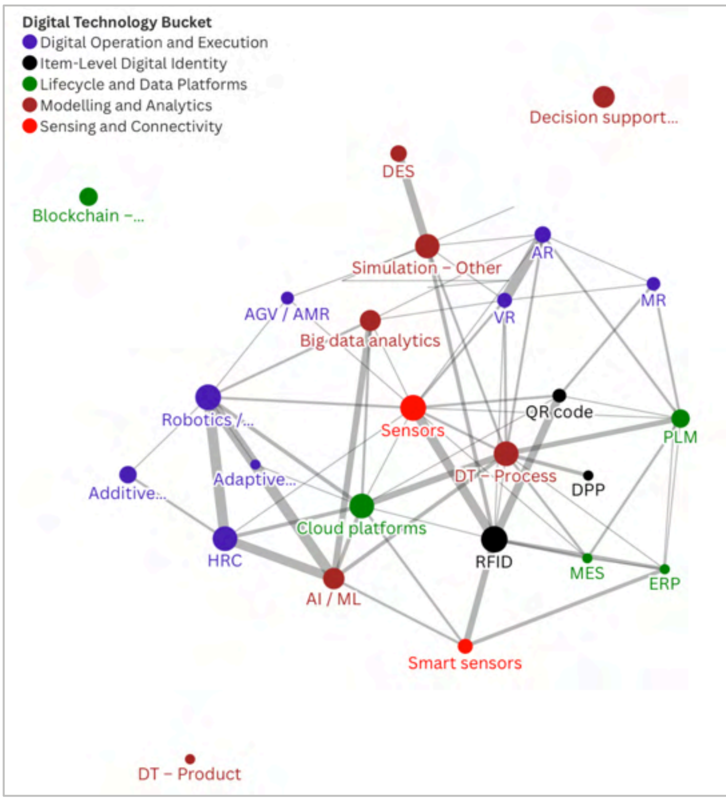


Figure 5. Co-occurrence network of digital technologies in remanufacturing research. Node size represents the number of times a technology is mentioned in the corpus, edge thickness indicates the frequency of co-occurrence within the same study, and colours correspond to the five digital technology buckets described above. The network immediately shows that process-level digital twins, cloud platforms, and big data analytics form central hubs through which most other technologies are connected. In contrast, decision support systems, blockchain for process traceability, and digital twins at product level appear more peripheral and are not directly integrated to other software or production system in the coded corpus. To improve the readability of the visual, technologies mentioned fewer than twice in the corpus are not mapped here. Technologies embedded within higher-level systems are coded only at the highest functional level to prevent double counting.

This leads to our first key finding that digital technologies in remanufacturing are fragmented and rarely connected end-to-end. Most studies focus on solving isolated problems, such as process planning, inspection, or scheduling, without demonstrating how information flows across the full system. For example, several papers implement simulation or optimisation tools using historical or static data, but these tools are not connected to live sensing systems or to execution technologies on the shopfloor. Other studies demonstrate robotic or human–robot collaboration cells, but these are not linked to enterprise systems or product history. Where multiple technologies are mentioned in the same paper, they are often presented as parallel components rather than as an integrated workflow. Evidence shows low integration levels, indicating standalone or loosely connected solutions rather than coordinated systems.

Next, the network is decomposed into sub-networks that isolate the interaction of item-level digital identity with lifecycle platforms and operational technologies. Figure 6 on the left shows identity (black nodes) and lifecycle and data platforms (green nodes). RFID and QR are connected to ERP, PLM, MES, and cloud platforms, indicating that basic identification mechanisms are at least partially embedded within enterprise systems. In contrast, the Digital Product Passport (DPP) is disconnected, suggesting that while it is discussed conceptually as a persistent and dynamic product identity, it is not yet meaningfully integrated into lifecycle management infrastructures.

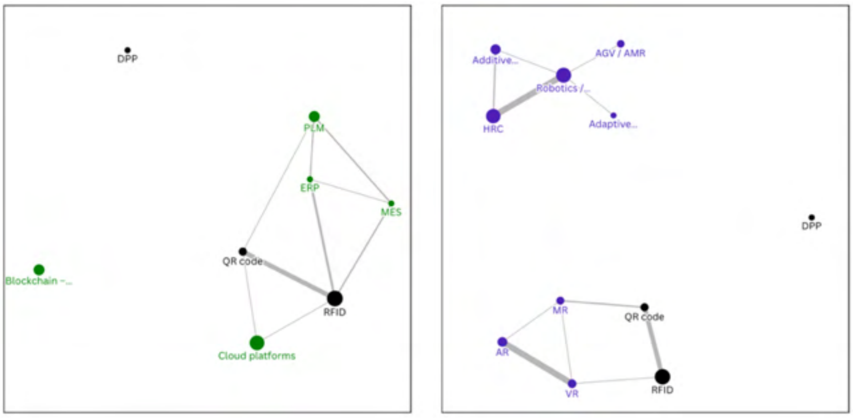
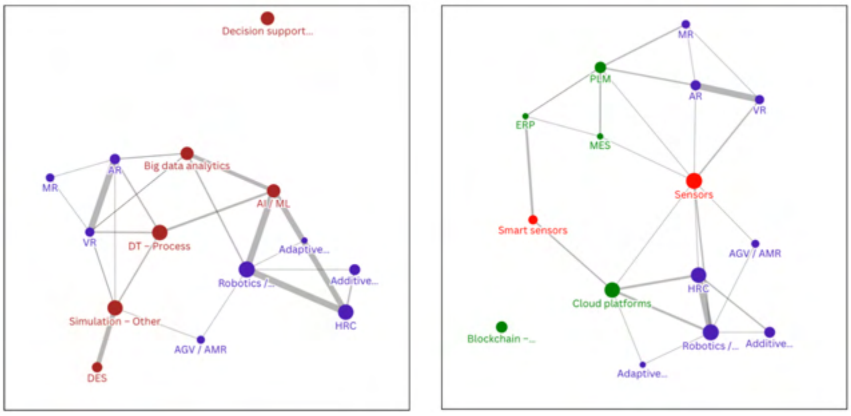


Figure 6. Sub-network on the left shows the interaction between item level digital identity technologies (black) and life cycle and data platforms (green). Sub-network on the right illustrates the relationship between item level digital identity (black) and digital operation and execution technologies (purple).

This supports the earlier observation of interoperability gaps, where product identity may exist, but updates reflecting changes across the product's lifecycle are not systematically connected to enterprise platforms. The figure on the right highlights the weak linkage between item-level identity and digital operation and execution technologies. Although immersive tools such as AR, VR, and MR co-occur with RFID and QR codes, these links appear confined to localised use and are not structurally integrated with operational technologies like robotics or machining. In other words, identity technologies are often used to read information but not to update it, which limits their potential to be leveraged across the full lifecycle and execution architecture required for integrated remanufacturing.

Figure 7. Sub-network on the left shows the interaction between modeling and analytics (brown) and digital operation and execution (purple). Sub- network on the right shows the interaction between sensing and connectivity (red), lifecycle and data platforms (green) and digital operations and execution (purple).



The next two isolated sub-networks illustrate areas where integration appears stronger yet still reveal structural gaps specific to remanufacturing. The figure on the left, linking modelling and analytics technologies with digital operation and execution, shows a tightly connected core linking simulation, process-level digital twins, AI/ML, robotics, and human–robot collaboration. This configuration mirrors established smart manufacturing architectures in which analytics and automation operate in a coordinated loop. However, decision support systems remain peripheral, suggesting that remanufacturing-specific decision logic is often developed conceptually or as a standalone layer rather than embedded within the operational workflow. On the right, the network combining sensing, lifecycle platforms, and execution similarly reflects a conventional industrial backbone: sensors connect to PLM, MES, ERP, and cloud platforms, which in turn link to execution technologies. Yet blockchain-based traceability and product-level digital twins remain weakly integrated, indicating that evolving product histories and item-specific state information are not systematically connected to enterprise systems or live operations.

The analysis of the sub-networks points towards the need for a fundamental shift in perspective rather than a shortage of technological capability. In conventional manufacturing, where the main aim is to reduce process variability and improve productivity, digital systems are organised around processes, typically interacting locally and sequentially along the production flow. Remanufacturing requires a different architecture. The product, which drives process variability, must become the central organising principle. A dynamic product identity should remain continuously connected to sensing systems, analytics, execution technologies, and lifecycle platforms, so that information evolves as the product moves through each stage.

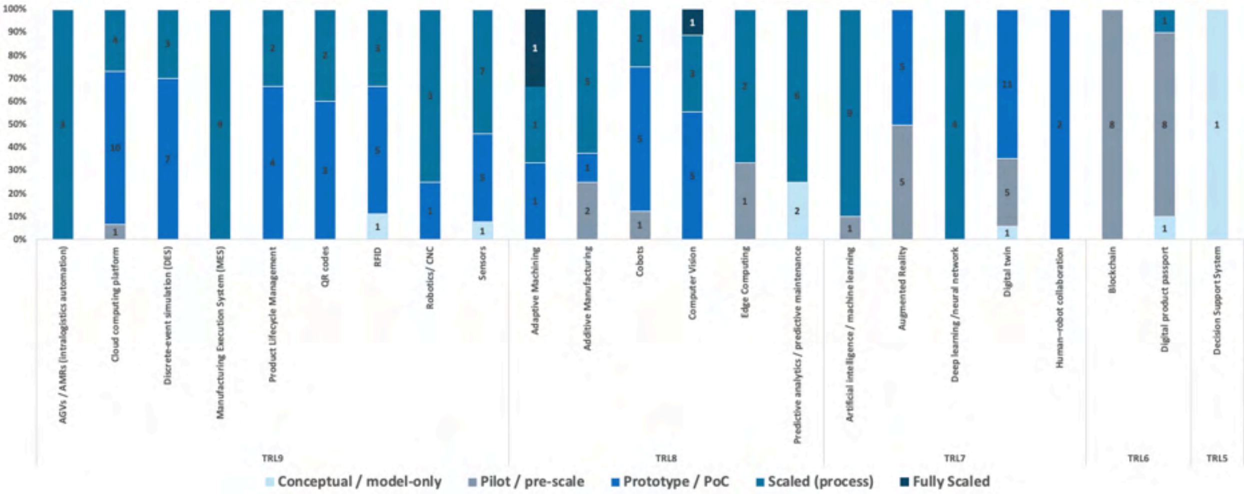


Figure 8. This figure shows the distribution of reported implementation maturity levels for each technology family grouped by the technology readiness level. Most technologies fall within TRL7 to TRL 9 indicating that they are technically mature, however a majority of reported applications remain at prototype, proof of concept or process level scale rather than full operational deployment. Evidence derived from systematic literature reviews is not included in this chart as the focus here is on reported implementation cases rather than review based discussions.

The technologies appearing in these studies are highly mature in manufacturing or other application contexts. Sensors, RFID, simulation, optimisation, robotics, cloud systems, and enterprise platforms all have long histories of industrial use, and many have a technological readiness level close to full operational maturity. Yet the evidence base concentrates on prototypes, proofs-of-concept, and process-level deployments, with only one example demonstrating an integrated remanufacturing process at full scale (from core acquisition to sale of the remanufactured product), and even this case combining only a limited set of technologies. This concentration of process-level maturity further reinforces a process-centred framing of technology application in remanufacturing, where a single step is improved (often using robotics and automation) without addressing the end-to-end system.

Taken together, these findings suggest that technologies already exist, but the gap is integration readiness and targeting the key reinforcing barriers to solve with these, which as indicated by the causal loop diagram is product lifecycle optimisation and not merely process automation.

INNOVATION ACTIVITY ALSO SIGNALS SCALABILITY GAPS

This section brings the analysis from academic research into the real world. The earlier parts of this white paper used a systematic literature review to identify the main barriers to remanufacturing and repair, and a causal loop diagram to understand how these barriers reinforce each other. However, academic work often focuses on concepts, models, and controlled examples. To understand what is being built, tested, and funded today, we analysed innovation projects supported by Horizon Europe. Horizon projects provide a useful lens because they sit at the intersection of research, industry, and policy. They show which problems are considered fundable, which technologies are prioritised, and which types of solutions are being tested in practice.

ONLY 70 PROJECTS IN THE HORIZON PORTFOLIO ADDRESS REMANUFACTURING, REPAIR OR REFURBISHING

The analysis was conducted on a filtered Horizon portfolio of 978 projects drawn from four programme areas where digital innovation and industrial application are most visible: Twin Transition, Digital and Emerging, EIC Pathfinder, and EIC Transition programmes.

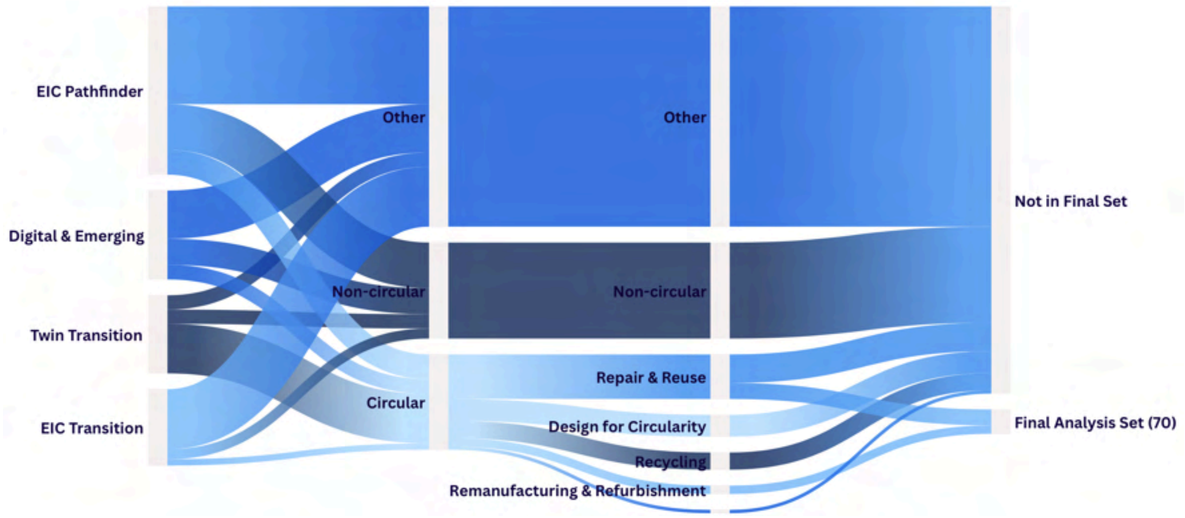


Figure 9. The Sankey Diagram shows how projects from four horizon funding streams with key focus on digital technology development were filtered and classified based on their circular economy impact. Projects that developed or demonstrated technologies to support circular economy were further classified based on their key activities. Seventy projects were selected for analysis – while only ten projects have a core Remanufacturing focus, circularity focused projects that addressed some of the shared barriers were also considered for deep-dive analysis.

Across these four areas, the portfolio contains a wide range of innovation. Some projects focus on sustainability and circular economy, while others focus on digital competitiveness, industrial efficiency, health, energy, or social challenges. To make a meaningful comparison, we first grouped all projects into three broad categories: circular economy projects, non-circular industrial innovation projects, and other projects that fall outside the scope of industrial circularity, such as health and medicine or general societal themes. Out of the 978 projects, 222 were classified as circular economy projects. A further 159 were classified as non-circular industrial innovation. The remaining 597 projects, categorised as other, were not comparable to industrial innovation activities. We then looked more closely at the 222 circular economy projects. These projects were not all working on the same aspects of the circular economy. Some focused-on recycling, some on design, some on new business models, and some on repair or remanufacturing. When we grouped them by their main circular activity, only 20 projects focused directly on remanufacturing and refurbishing. A further 58 projects focused on repair and reuse. Repair is an important part of remanufacturing capability: skills, data, and technologies developed for repair are often prerequisites for remanufacturing. For this reason, we analysed these two groups together. After excluding projects where repair referred to medical or biological repair, this resulted in a final set of 70 projects.

This means that out of 978 projects in the filtered Horizon portfolio, only 70 projects directly address the activities that are most closely linked to remanufacturing or circular economy. This represents just over seven percent of the portfolio.

DIGITAL AND EMERGING PROGRAM SHOWS A CLEAR TENSION FOR CIRCULAR ECONOMY FUNDING

At first glance, the Horizon portfolio appears to support circular economy innovation quite strongly. This impression is largely driven by the Twin Transition programme, which is explicitly designed to link digital innovation with sustainability objectives. In the Twin Transition, most projects have a circular focus.

The picture changes when we look at the Digital and Emerging programme. This programme is designed to strengthen digital and industrial competitiveness across Europe and is not primarily a sustainability programme. Within Digital and Emerging, there are 212 projects in the dataset. Of these, 35 projects are circular economy projects, 62 are non-circular industrial innovation projects, and 115 fall into other non-comparable categories such as health or energy. If we remove the non-comparable categories and focus only on projects that are comparable from an industrial perspective, the Digital and Emerging portfolio contains 97 projects. Within this set, only 35 projects are circular economy projects. The remaining 62 projects support non-circular industrial pathways, i.e., the linear economy. In other words, within the comparable Digital and Emerging portfolio, almost two thirds of projects focus on strengthening non-circular industrial pathways.

When we look inside the circular share of Digital and Emerging, a further skew appears. Out of the thirty-five circular projects in this programme, seventeen focus on recycling. Only two projects focus explicitly on remanufacturing and refurbishing. This matters because Digital and Emerging funding shapes future industrial capabilities. When innovation simultaneously strengthens the unit-cost economics of linear value chains, it exacerbates the competitiveness gap between circular and linear business models. This creates a risk that digital innovation strengthens linear competitiveness faster than it strengthens circular systems. Furthermore, when circular economy innovation is weighted towards recycling and downstream recovery, upstream intervention strategies receive far less attention.

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INNOVATION FOCUS IS ON MANAGING UNCERTAINTY AND DOWNSTREAM EFFICIENCY

The causal loop diagram shows that uncertainty at the point where a product arrives drives many downstream problems. Missing product history, unknown condition, complex disassembly, and unstable return flows increase process variability. This reduces economic viability and slows investment in capability building.

We mapped the 70 projects against the key intervention points in the causal loop diagram to see where Horizon-funded innovation is concentrating. The strongest coverage is found in areas that are easier to generalise across industries: 56/70 projects address poor business case, 54/70 address stakeholder coordination, and 39/70 address sequencing and process variability. In these areas, digital platforms, artificial intelligence, robotics, and digital twins are frequently deployed as optimisation and coordination tools.

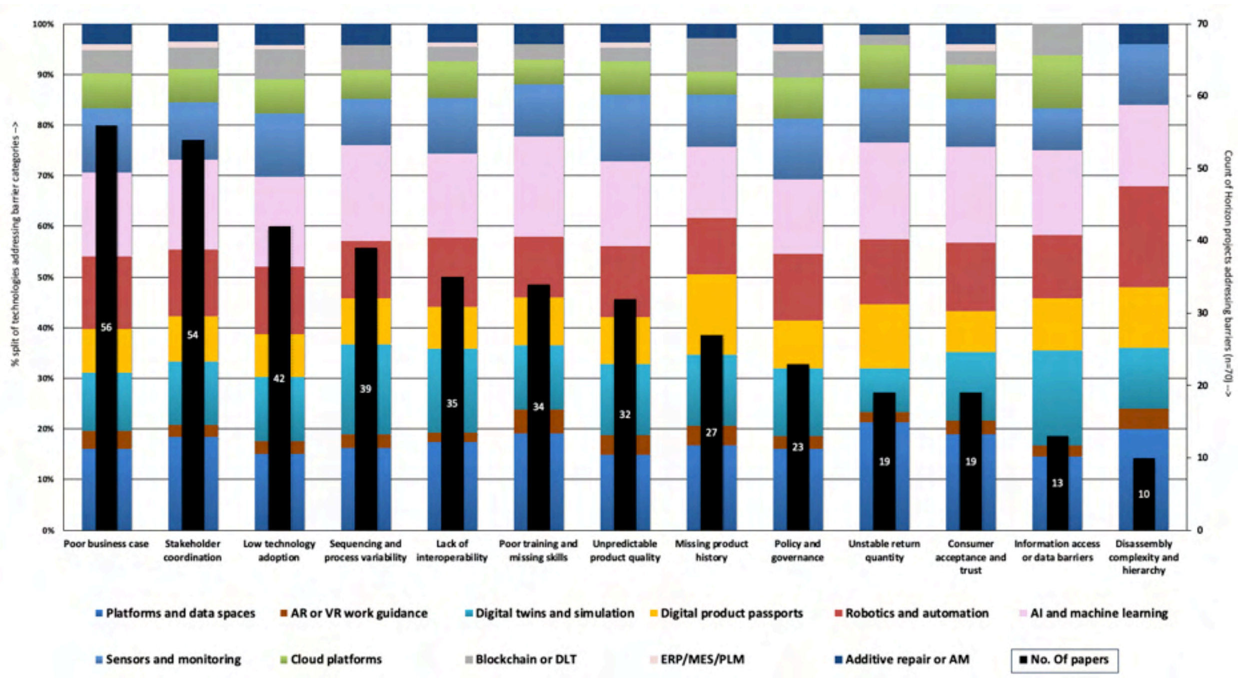

Figure 10. Stacked bars show the most frequently cited technologies addressing each barrier in the 70-project corpus. The primary axis represents thick coloured stacks corresponding to technology evidence counts, while the central grey narrow stacks on the secondary axis indicate the count of projects addressing a certain barrier category.. Stakeholder coordination and consumer trust and acceptance, a barrier not addressed through application of technologies in the academic corpus, are tackled in real projects.

Only moderate attention is given to workforce skills, unpredictable product quality, missing product history, and interoperability. For example, only 34/70 projects address poor training and missing skills, 32/70 address unpredictable product quality, and only 27/70 address missing product history. When we look closely at the technological mix, we also see that solutions often rely heavily on artificial intelligence, robotics, and digital twins, while ERP and lifecycle-integration layers are rarely present. Only two projects link poor business case interventions to ERP or MES systems. Only one project connects interoperability challenges to enterprise systems. This gap matters because remanufacturing is not a standalone technical process. It is a networked activity across manufacturers, service providers, logistics actors, and downstream markets. Without clear integration pathways, digital solutions remain pilots rather than scalable systems. A similar pattern appears in traceability. While 28/70 projects address product history or traceability, this means that in more than half of the projects, product identity and lifecycle history are not treated as core design requirements.

TECHNOLOGY PROGRESS IS STRONG, YET SOCIO-TECHNICAL READINESS AND LIFECYCLE INTEGRATION LAG

To understand whether integration levels differ between remanufacturing projects and other circular economy projects, we analysed ten projects that explicitly focus on remanufacturing. We went beyond their CORDIS summaries and examined project websites, public deliverables, and, where available, statements provided by project partners. The aim was not simply to identify whether digital technologies were mentioned, but to assess how deeply they were implemented and how coherently they interacted as a system.

We assessed the ten projects along two dimensions. The first dimension was depth, which captured how mature and technically developed the digital solution appeared to be. The second dimension was range, which captured how broadly the solution was demonstrated and how ready it was to operate under real remanufacturing conditions.

To ensure consistency across projects, we defined two sets of five factors. The first set covered technology clusters and reflected depth of technical development across key digital themes. The technology clusters were as follows :

- Robotics and automation, covering the use of automation in handling, disassembly, repair, and related operations.
- AI and data for decision-making, covering analytics or AI used to support triage, routing, inspection, or other operational decisions.
- Digital thread and traceability, covering persistent identification and data continuity across items, processes, and stakeholders.
- Platforms and ecosystem, covering digital infrastructure that connects actors, data, and workflows, including coordination and interoperability.
- AR, VR, MR and machine vision, covering operator guidance, visual inspection, perception, and related human and machine interfaces.

The second set covered socio-technical readiness factors and reflected range and deployment conditions that shape real-world uptake and scaling. Socio-technical readiness factors were as follows :

- Human-in-the-loop flexibility, capturing whether the solution supported different modes of human involvement. This included fully automated approaches, hybrid decision support, and collaborative human and machine working. This factor matters because remanufacturing is variable and exception-heavy, and solutions often need to accommodate different operational realities.

- Demonstrator range, capturing the diversity of industry sectors used as demonstrators. Range was low when demonstrators were narrowly similar and high when demonstrations spanned materially and operationally distinct sectors.
- Replicability, capturing how readily others could reproduce and deploy the approach. It considered data needs, integration burden, and reliance on bespoke engineering or tacit expertise.
- Impact across the triple bottom line, capturing the extent to which economic, environmental, and social impacts were evidenced. Social outcomes were often the least consistently quantified.
- Lifecycle integration, capturing whether the innovation was applied across multiple stages of the product and remanufacturing lifecycle, rather than remaining confined to a single step.

	Project	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10
Technology Clusters	Robotics & Automation	8	5	8	4	9	4	4	4	5	2
	AI/Data (Decision)	7	8	7	7	8	7	7	7	7	4
	Digital Thread (Traceability)	7	8	7	7	7	7	7	7	7	4
	Platforms/ Ecosystem	4	5	5	7	8	5	5	5	7	5
	AR/VR/MR/ Machine Vision	7	8	7	4	8	4	8	4	7	2
Socio-technical readiness	Human-in-Loop	4	8	5	7	8	2	8	3	9	2
	Demonstrator Range	3	4	6	6	5	3	5	5	4	7
	Replicability	5	6	5	7	9	4	6	5	6	8
	Impact/ Triple Bottomline	3	5	4	4	5	3	4	3	3	8
	Lifecycle Integration	5	8	7	6	8	4	5	6	7	4

Figure 11. The heatmap summarises project performance across technology and socio-technical readiness factors and suggests a recurring trade-off- projects that score strongly across multiple technology clusters often show weaker performance in at least one socio-technical readiness dimension.

The scores presented in the heat map are based on publicly available materials, including information published on the Horizon platform, project websites, and public deliverables where available. For each criterion, the highest observed level of delivery across the ten projects was used as the practical benchmark and scored at eight or nine, while ten was reserved for projected long-term impact. Other projects were scored relative to that benchmark and rated as equal to it or lower. The impact scores therefore reflect what projects have evidenced and reported publicly, rather than constituting an audit of realised outcomes.

The heat map shows that projects scoring strongly across several technology clusters often score lower on one or more socio-technical readiness factors. Other projects perform well on socio-technical readiness but tend to concentrate on a narrower technology focus. Several project-level examples illustrate this pattern. Project 5 shows the strongest overall balance across the combined factors, but its demonstrators are concentrated in a relatively narrow industrial context, typically covering metallic components of their own known brands. Project 9 places substantial emphasis on upskilling and human-in-the-loop working, but it also scores lower on demonstrator range and on the quantification of impact. This reduces the strength of its scaling narrative. Project 10 focuses on demonstrating the impacts of circular and remanufacturing practices, and it scores highest on replicability and impact. It also focuses narrowly on eco-design and explores digital twins and product passports in a supporting context, but scores lower on lifecycle integration as it does not apply technologies to realise the lifecycle opportunities enabled through design for remanufacturing.

THE CURRENT STATE OF DIGITAL REMANUFACTURING AND FUTURE OPPORTUNITIES

FOCUS ON INDUSTRY SECTORS BEYOND WHERE REMANUFACTURING IS ALREADY CONCENTRATED

Both the academic literature and the Horizon project portfolio show a clear concentration of remanufacturing and repair activity in a small number of industry sectors. These are sectors where products are high value, technically complex, and already supported by service networks.

The strongest focus today is on industrial machinery and manufacturing equipment, automotive and mobility, construction and the built environment, and selected energy-related assets, such as wind components or electrical equipment. These sectors dominate both research publications and Horizon demonstrators because they combine long product lifetimes, measurable economic value, and existing maintenance practices that can be extended towards remanufacturing.

This concentration is understandable. These sectors provide relatively controlled environments in which remanufacturing can be tested. They also benefit from clearer ownership structures and better access to product data. However, this focus also creates a risk: it reinforces remanufacturing in sectors that are already comparatively well organised, while leaving other strategically important sectors under-explored.

INDUSTRY SECTORS WHERE REMANUFACTURING SHOULD PLAY A LARGER ROLE

Current geopolitical and economic pressures point to several sectors where remanufacturing could become strategically significant, yet investment remains limited. Energy transition infrastructure, including heat pumps, grid equipment, power electronics and storage systems, is expanding rapidly under material constraints and carbon reduction targets. Remanufacturing can reduce reliance on virgin inputs, shorten lead times and lower embodied emissions. Enterprise ICT and data centre hardware present a similar opportunity. As digital infrastructure grows, servers and network systems already circulate through informal markets with limited traceability. Structured remanufacturing supported by digital lifecycle data could improve reliability, compliance and carbon performance. Digital Product Passports are already mandated for batteries under the EU Battery Regulation and will extend to categories such as consumer electronics, ICT equipment and other products under the Ecodesign for Sustainable Products Regulation. These sectors include electric vehicle batteries, industrial batteries, smartphones, laptops, servers and large appliances. Where lifecycle data, material composition and carbon footprints must be digitally documented, the structural foundation for closed-loop recovery and remanufacturing is effectively created. In these sectors, compliance-driven traceability can become a direct enabler of scalable remanufacturing systems.

Beyond these domains, highly carbon-intensive and regulated industries warrant greater attention. Heavy industrial equipment in mining, steel and cement production, along with aviation, rail and petrochemical systems, operate under tightening emissions and reporting obligations. These sectors rely on complex, high value components that are frequently replaced rather than restored. Remanufacturing, supported by robust digital traceability and condition assessment, could reduce embodied carbon while strengthening compliance and performance verification. In these contexts, remanufacturing is not only a circular strategy, but a mechanism for meeting environmental and regulatory expectations at scale.

DIGITAL TECHNOLOGIES TO BE POSITIONED AS BOTH BARRIER SOLVERS AND OPPORTUNITY ENABLERS

Much of the current discussion frames digital technologies as tools to overcome barriers, such as uncertainty, complexity, and lack of coordination. The Horizon portfolio reflects this. Artificial intelligence is used to improve inspection and diagnosis. Digital twins support planning and simulation. Platforms aim to coordinate actors and data. However, the same technologies also create opportunities that go beyond problem-solving.

- Digital traceability and product identity systems can support environmental and social reporting by capturing evidence across the lifecycle. This can reduce reporting burden, increase credibility, and improve alignment with regulatory frameworks. In turn, this can support consumer trust and procurement decisions.
- Decision support systems that integrate technical, economic, and environmental data can help firms respond more quickly to policy changes and market shocks. This supports business continuity and reduces risk when legislation evolves.
- Integrated digital systems can also help shift remanufacturing from a cost-saving activity to a strategic capability. When lifecycle data, performance evidence, and quality assurance are visible and auditable, remanufactured products can compete on reliability and value, not only on price.

In this sense, digital technologies are not only tools to manage barriers. They can also strengthen key drivers, including consumer acceptance, regulatory compliance, and strategic resilience.

EMERGING TECHNOLOGIES NOT YET APPLIED TO REMANUFACTURING

The Horizon portfolio shows strong use of established digital technologies, such as machine learning, robotics, and simulation. At the same time, several emerging technologies that are already used in other fields remain largely absent from remanufacturing research and practice.

- Advanced decision systems, including agent-based and autonomous planning approaches, are increasingly used in logistics, energy systems, and finance. These systems could support intake decisions, routing, and prioritisation in remanufacturing, where variability is high and manual decision-making is costly.

- Privacy-preserving data technologies, such as federated learning and secure computation, are being applied in healthcare and finance to enable collaboration without data leakage. These approaches could help overcome trust and intellectual property concerns that currently limit data sharing in remanufacturing ecosystems.
- Distributed digital credentials and verifiable records are emerging in identity management and supply chain security. Applied to remanufacturing, they could support warranty, authenticity, and compliance without relying on centralised control.
- More speculative technologies, such as quantum optimisation, are being explored in manufacturing scheduling and materials science. While still immature, they point to future capabilities in handling complex optimisation problems under uncertainty, which are central to remanufacturing systems.

The absence of these technologies from current remanufacturing projects does not imply failure. It indicates that the field is still focused on building foundations. However, it also highlights clear directions for future research and innovation.

FROM TECHNOLOGY READINESS TO PRODUCT CENTRIC INTEEGRATION

The evidence presented in this report leads to a clear conclusion. Digital technologies relevant to remanufacturing are not missing. Sensors, artificial intelligence, robotics, simulation tools, enterprise platforms and lifecycle systems are already mature and widely used in conventional manufacturing. Yet in remanufacturing they are rarely integrated end to end. Applications remain localised, process focused and often conceptual. The result is a landscape characterised by strong digital components but weak architectural coherence.

The first and most immediate opportunity lies in applying the existing suite of industrial technologies differently. Low hanging gains can be achieved by shifting the organising principle from process to product. Identity, sensing, analytics and execution must remain continuously connected as the product moves through inspection, decision making, restoration and validation. Enterprise systems must not sit at the periphery but form part of an integrated digital backbone. When deployed through a product centric logic, current technologies can reduce uncertainty, strengthen planning reliability and improve the business case without waiting for new inventions. At the same time, remanufacturing remains intrinsically complex. Even with improved integration, high variability, distributed actors and circular value chains create challenges that differ fundamentally from linear production. Future research and innovation must therefore go beyond adoption and focus on developing digital systems specifically designed to manage uncertainty. This includes adaptive decision architectures, secure multi actor data infrastructures, dynamic product identity mechanisms and governance models suited to circular ecosystems.

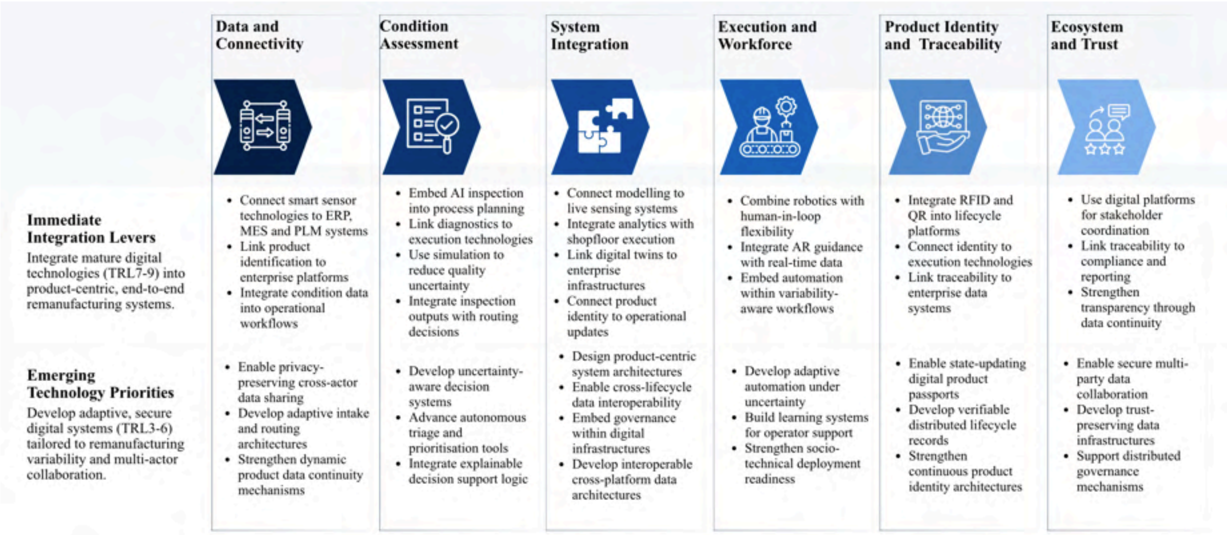

Figure 12. Future research avenues for advancing digital remanufacturing. The figure distinguishes two complementary pathways. The first focuses on immediate integration levers, demonstrating how existing technologies can be applied to deliver rapid gains in remanufacturing. The second identifies emerging technology priorities, highlight areas where bespoke digital solutions are required to manage high variability, multi-actor coordination and lifecycle complexity inherent to remanufacturing.

Moving forward requires treating remanufacturing not as a variation of linear production, but as a distinct operational paradigm shaped by variability, distributed actors and compliance pressure. If digital systems are designed around these realities, remanufacturing can shift from a constrained circular practice to a credible industrial strategy for resilience, competitiveness and carbon reduction.

CONTRIBUTION STATEMENT

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Author contributions are described according to the CRediT (Contributor Roles Taxonomy) framework :

- Priya Saikumar conceived the study and developed the research methodology. She conducted the investigation, curated and analysed the data, developed the system dynamics modelling and visualisations, and led the writing of the original manuscript as well as subsequent revisions.
- Erik Soerqvist contributed to the investigation and data curation and supported the collection and analysis of Horizon project data. He also reviewed and contributed to revisions of the manuscript.
- Prof. Lucia Corsini supervised the research and provided methodological guidance. She contributed to the validation of the analytical approach and reviewed the manuscript.

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ENDNOTES & REFERENCES

1. The full coded academic corpus of 55 peer-reviewed studies, including barrier classifications and technology mappings, is available via the Open Science Framework repository: https://doi.org/10.17605/OSF.IO/F34AQ
2. The Horizon portfolio screening dataset of 978 projects, the filtered set of 70 circular economy projects, and the detailed qualitative assessment of 10 remanufacturing-focused projects are available via the same Open Science Framework repository: https://doi.org/10.17605/OSF.IO/F34AQ
3. The system dynamics model, including variable definitions and reinforcing feedback loops R1 to R8, was developed using Stella Architect. An interactive version of the model can be accessed at: https://exchange.iseesystems.com/diagrams/player/priya-saikumar/remanufacturing
4. The technology co-occurrence and dependency network visualisation was developed using Flourish. The interactive version can be accessed at: https://public.flourish.studio/story/3587367/
5. Afari, J. A., Gosavi, A., Hu, J. et al. (2025) ‘Data-driven layout design for smart remanufacturing: a flexible optimization model and a case study’, International Journal on Interactive Design and Manufacturing, 19, pp. 8625–8639. https://doi.org/10.1007/s12008-025-02296-5
6. Chai, Q., Sun, M., Lai, K. H. and Xiao, Z. (2023) ‘The effects of government subsidies and environmental regulation on remanufacturing’, Computers and Industrial Engineering, 178, 109126.
7. Chau, M. Q., Nguyen, X. P., Huynh, T. T. et al. (2025) ‘Prospects of application of IoT-based advanced technologies in remanufacturing process towards sustainable development and energy-efficient use’, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 47(2). https://doi.org/10.1080/15567036.2021.1994057
8. CLEPA (2022) European Remanufacturing Market Study. Brussels: CLEPA.
9. De Simone, V., Luisi, G., Macchiaroli, R., Fruggiero, F. and Miranda, S. (2024) ‘Artificial intelligence in remanufacturing contexts: current status and future opportunities’, in Fera, M., Caterino, M., Macchiaroli, R. and Pham, D. T. (eds.) Advances in Remanufacturing. Lecture Notes in Mechanical Engineering. Cham: Springer. https://doi.org/10.1007/978-3-031-52649-7_2
10. Dudkowiak, A., Grajewski, D. and Dostatni, E. (2025) ‘A systematic literature review of artificial intelligence methods in remanufacturing’, IEEE Access, 13, pp. 215897–215910. https://doi.org/10.1109/ACCESS.2025.3646974
11. European Commission (2023) Commission Staff Working Document accompanying the Proposal for a Directive on common rules promoting the repair of goods. Brussels: European Commission.
12. European Commission (2023) Regulation (EU) 2023/1542 concerning batteries and waste batteries. Brussels: European Union.

13. European Commission (2024) Ecodesign for Sustainable Products Regulation. Brussels: European Union.
14. European Commission (2024) EU Clean Industrial Deal. Brussels: European Commission.
15. European Remanufacturing Council (2020) European Remanufacturing Market Study.
16. Kim, Y. H., Ye, W., Kumar, R. et al. (2024) 'Unlocking the potential of remanufacturing through machine learning and data-driven models: a survey', Algorithms, 17(12), 562. https://doi.org/10.3390/a17120562
17. Kerin, M. and Pham, D. T. (2020) 'Smart remanufacturing: a review and research framework', Journal of Manufacturing Technology Management, 31(6), pp. 1205–1235. https://doi.org/10.1108/JMTM-06-2019-0205
18. Okorie, O., Charnley, F., Ehiagwina, A. et al. (2024) 'Towards a simulation-based understanding of smart remanufacturing operations: a comparative analysis', Journal of Remanufacturing, 14, pp. 45–68. https://doi.org/10.1007/s13243-020-00086-8
19. Policy Connect (2020) Triple Win: The Social, Economic and Environmental Case for Remanufacturing. London: Policy Connect.
20. Saikumar, P. (2025) Digital Technologies in Remanufacturing – Supporting Data. Open Science Framework. https://doi.org/10.17605/OSF.IO/F34AQ

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