Remanufacturing business growth with supply-demand AI forecasting and data sharing

D1.1 Business Drivers and Growth in Remanufacturing Market

Document Information

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Purpose of this document

This document targets to the future remanufacturing markets, its challenges, drivers and regulation that shapes the remanufacturing sector. The document focuses particularly on developments in automotive, non-road mobile machinery and adjacent industrial contexts where long product lifetimes, high-value components and growing data intensity are reshaping remanufacturing opportunities.

The assessment brings together evidence from business intelligence sources, European policy and regulatory documentation, academic literature and company-level reference cases and provides an overview of the current state of the remanufacturing market. The report is structured around markets, sector-specific dynamics, actor roles, business drivers and restraints, technology developments, core acquisition management, regulation and standards, industrial reference programmes, and implications for future industrial value creation. Special attention is given to the role of artificial intelligence (AI), particularly its impact on market development, operational efficiency and new data-driven business models in remanufacturing.

The report applies the PESTEL framework, covering political, economic, social, technological, environmental, and legal factors that influence business growth. This approach provides a structured analysis of how remanufacturing markets may evolve, the key drivers shaping these markets, and the conditions required for remanufacturing to become a core business activity.

The document results are used in FREIMAN project to provide the state of the art in remanufacturing and the current state of the industry. It will be used as information source in the next phases of the project (Figure 1) especially in task 1.2 that concentrates on new remanufacturing opportunities with components, technologies, partners and business models on more practical level. Findings support also the development of potential business use cases and the related sustainability opportunities and targets in task 1.3. Overall, this document provides important market insight and business intelligence information for the project.

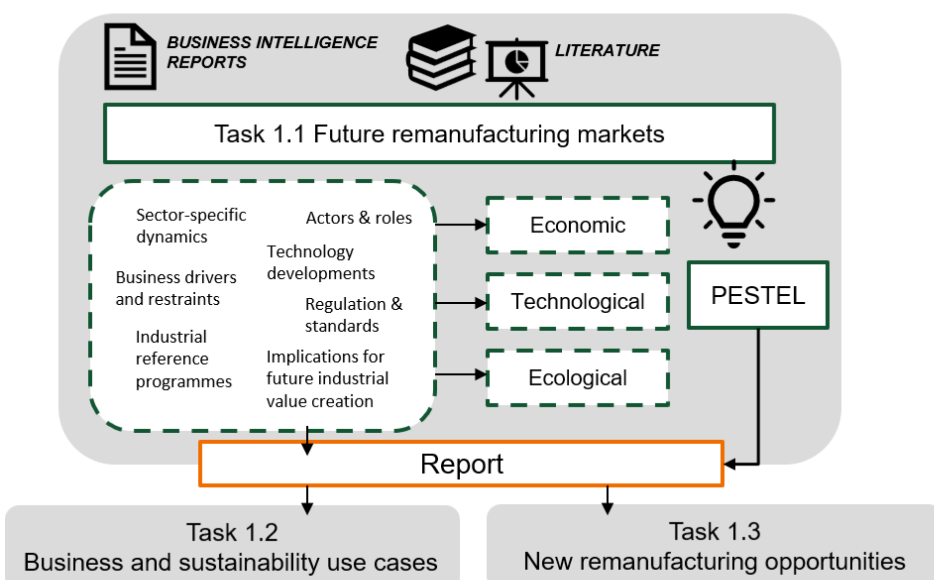

Figure 1. Task 1.1. report – Layout and linkages.

1 Remanufacturing markets

In this deliverable, remanufacturing is understood as an industrial process through which used parts, components or products are restored under controlled procedures to a condition that is equal or better than their original state, ensuring they meet or exceed the original performance specifications. Remanufacturing process is typically supported by returning, disassembly, inspection, replacement of worn elements, testing and quality assurance [1]. This distinguishes remanufacturing both from repair, which may restore only immediate functionality, and from recycling, which recovers raw material value after product end-of-life. Remanufacturing preserves a larger share of embedded product value and therefore occupies a strategically important position in circular industrial systems [2].

1.1 Market overview and growth outlook

Remanufacturing represents a large and expanding global market. Estimates indicates that the global remanufacturing market already exceeds USD 100 billion and is growing across multiple industries. Reported estimates vary substantially depending on sectoral coverage and methodology, ranging from USD 97,5 billion in 2019 to USD 257,3 billion in 2023 with a reported compound annual growth rate (CAGR) of 5,4 % [3] and from USD 425 billion in 2024 toward USD 896 billion by 2029 with a reported compound CAGR of 25,5 % [4]. At the European level, the European Remanufacturing Network has estimated market potential of 100 billion euros by 2030 [5].

The market outlook is not uniform across sectors. Automotive remains the most developed remanufacturing domain and therefore provides an important benchmark. Automotive remanufacturing market is estimated to be around USD 80 billion in 2025, rising to approximately USD 185 billion by 2034 [6]. Non-road mobile machinery is also a significant related market, estimated at around USD 66,2 billion in 2025 and approximately USD 95 billion by 2035 [7]. The forestry equipment market is smaller in absolute terms, but still strategically relevant, in the range of USD 9 - 12 billion in 2025 and USD 11 - 15 billion by 2031 depending on provider and market framing [8], [9], [10]. Increased mechanised logging in emerging economies, rising demand for certified timber products, government re-afforestation incentives, electrification of off-highway fleets, labour shortages encouraging increased level of automation, and the deployment of digital twins for predictive maintenance are expected to support future demand in forestry equipment markets [8], [9], [10].

The sustainability rationale for remanufacturing is equally significant. The studies [11] report average savings of approximately 38 % in energy use, 96 % in raw materials, around 40 % in CO_2 emissions and approximately 40 to 60 % in costs relative to manufacturing a comparable new product. Annual material savings are also described as corresponding to roughly 14 million tonnes. Together, these indicators explain why remanufacturing is increasingly treated as a strategic industrial capability rather than a niche aftermarket activity. It contributes simultaneously to competitiveness, supply security and circular economy objectives.

1.2 Sector-specific dynamics: Automotive and non-road mobile machinery

Automotive remanufacturing is currently ahead of heavy-duty and off-highway sectors in terms of market maturity, standardisation, actor structure and customer acceptance. Automotive has benefited from high production volumes, relatively standardised component architectures, established aftermarket channels and more mature reverse logistics systems. These conditions support repeatable remanufacturing operations and more predictable access to returned cores, making scale easier to achieve.

By contrast, non-road mobile machinery and other heavy-duty domains operate under more heterogeneous conditions. Production volumes are lower, component portfolios are more specialised, and batch sizes are smaller. Core components are expensive, service conditions are demanding, and products remain in operation for long periods. Ownership models and maintenance responsibility can vary considerably, which affects when and how components return to the value chain. In addition, fragmented serialisation and incomplete lifecycle visibility can limit traceability and complicate condition-based decision-making. These features increase operational complexity but also strengthen the business case when remanufacturing can be successfully organised, because individual components often carry high residual value.

A key finding is that remanufacturing is progressing from restoring function towards a model focused on optimising lifecycle value through data and analytics. In practice, this means that maintenance history, operating conditions, condition assessment and product traceability increasingly determine whether, when and how a component should be remanufactured. The commercial opportunity therefore extends beyond workshop operations and depends on the ability to structure and exploit lifecycle information.

1.3 Regional trends and emerging business models

Regional patterns in automotive remanufacturing analysis suggest differentiated development pathways. North America and Europe are expected to lead investment in electric-vehicle-related remanufacturing, while Asia-Pacific functions as both a major sourcing and core export hub and a potentially high-growth market. Latin America is described as a fast-growing economy able to support external demand through manufacturing programmes and to expand domestic demand for conventional remanufactured components [12].

Within this picture, Europe is associated with original-equipment-initiated remanufacturing programmes, policy-driven standardisation and a growing focus on electric-vehicle and battery-related remanufacturing. North America shows similar strength in original-equipment-led programmes while also emphasising buy-back initiatives, replacement-linked rebates and private-label programmes. Asia-Pacific is characterised by strong sourcing capacity and continuing emphasis on high-value conventional components. Latin America is positioned as both an alternative sourcing region and an expanding domestic market [12].

Frost & Sullivan identifies six trends likely to shape the future circular economy of parts: stronger core acquisition and reverse logistics, consistent quality and regulatory frameworks, increased modularisation and serviceability, improved traceability and lifecycle management, future-proofing for connected and electrified components, and wider use of private labelling in the independent aftermarket [12]. These trends indicate that future market growth will depend on coordinated system capabilities that align product design, logistics, software access, authentication and commercial incentives.

1.4 Actors and competitive dynamics

The remanufacturing landscape is shaped by evolving relationships between original equipment manufacturers (OEM), Tier 1 suppliers, wholesalers, independent remanufacturers and core brokers. Automotive remanufacturing field is seen to remain dominated by Tier 1 suppliers and independent remanufacturers, but original equipment manufacturers are increasing their role as products become more digitalised and access to design data and software becomes more decisive [13].

Tier 1 suppliers are strengthening their remanufacturing position through contract work with original equipment manufacturers and through access to data and software needed to process increasingly complex products. Wholesalers are also moving into the remanufacturing space because they may have efficient access to large volumes of returned cores. At the same time, independent remanufacturers face growing challenges where reverse engineering is constrained by software dependence, restricted access to original design information or increasing product complexity, especially in relation to electric and electronically intensive systems [13].

Competition over returned cores is becoming strategically important. When original equipment manufacturers strengthen control over recovery channels and installed-base information, they also increase control over future remanufacturing capacity. This indicates a broader shift from transactional spare-parts business towards lifecycle-oriented business models based on installed-base visibility, customer relationships and control of reverse logistics [12], [13].

2 Challenges, drivers and new focus areas

2.1 Drivers of growth and market constraints

There are several reinforcing drivers of remanufacturing growth. Cost pressure and affordability demands remain important, particularly in economically volatile conditions. Sustainability and lifecycle-extension objectives are becoming more prominent as legislation and policy increasingly favour longer product use. Supply-chain disruption and raw-material scarcity improve the attractiveness of preserving existing asset value. Remanufactured components may also have lower production costs than new equivalents and can provide a viable option for end-users seeking to keep older machinery or vehicles in operation for longer periods [6], [11].

At the same time, significant barriers remain. Suitable core availability continues to be a foundational challenge. Without predictable returns, remanufacturing volumes remain difficult to plan and scale. The absence of mature reverse logistics and business-to-business partnerships increases uncertainty and cost. In some product categories, design choices and material combinations still limit efficient disassembly and remanufacture. Data availability and data quality may be insufficient for reliable condition assessment or process planning. Furthermore, market awareness remains uneven, and some customers continue to associate remanufactured products with uncertainty despite evidence of quality-controlled processes and warranty-backed offerings.

These growth drivers and barriers interact. Policy incentives for longer product life, for example, do not automatically create market expansion unless companies can also access product information, organise reverse channels and perform robust condition assessment. Similarly, condition monitoring and predictive analytics generate value only when commercial models and customer relationships allow the remanufacturer to influence return timing and component recovery. The enabling conditions for market growth are therefore organisational, technical and commercial at the same time.

2.2 Technology trends shaping future remanufacturing

Technology development is reshaping the remanufacturing opportunity space through key trends such as automation, electrification and digital integration. AI can support inspection, condition assessment and forecasting. Electrification changes the component base of machinery through batteries, power electronics, electric drives and hybrid powertrains. Remote and autonomous operation introduce additional dependence on communication systems, control logic and safety-relevant software.

One major aspect reshaping the markets is AI. In general, it transforms machines, products and processes into smart entities enabling predictive maintenance, real-time monitoring and process optimization [14], [15]. AI already plays a role in manufacturing and continues to grow [16]. The role will also increase in remanufacturing sector and markets. The contribution is AI-driven supply chain optimisation, enabling customisation and flexibility of the manufacturing. Use of AI can lead to increased productivity and efficiency of the processes and reduced failures [16].

The use of AI technologies can be implemented in multiple phases of the industrial asset or machine. For extending the product life cycle and material circulation, AI can be used already in maintenance phases to prevent early disposal of use. AI can be used for fault diagnostics, future behaviour predictions and to estimate the remaining useful life [17]. Estimating the remaining useful life is beneficial for estimating the remanufacturing loops. Before entering the remanufacturing stage, the assets and components can be retrofitted considering AI technologies by adding e.g., real-time monitoring, data exchange and intelligent control that enables the component to become a part networked system [17].

These developments alter the value profile of returned cores. In traditional remanufacturing settings, value has often been concentrated in mechanical integrity, wear behaviour and the recoverability of material-intensive components. In future systems, value increasingly also resides in embedded software, interfaces, sensors, communication functions and historical operating data. Real-time data transfer and connectivity can support more accurate timing decisions, better maintenance planning and improved expected remanufacturing yields. Digital twins may connect operation, servicing, redesign and remanufacturing in a more continuous lifecycle information loop.

Technological development also indicates that remanufacturable component portfolios are expanding. Established remanufacturing domains include engines, hydraulic systems, transmissions and drivetrains. In the near future, next three to seven years, stronger remanufacturing activity is expected in power electronics, mechatronic actuators and electronic control units. Beyond that horizon, sensor systems, embedded intelligence, connectivity modules, safety-critical electronic systems and software-defined hardware could be the next frontier. This suggests that remanufacturing markets increasingly follow technology domains rather than individual machine categories, creating opportunities for cross-sector capability development.

2.3 Core acquisition management and new business focus areas

Core acquisition management emerges as a central future challenge. The main difficulty lies in uncertainty regarding the timing, volume and quality of returned cores. Return timing depends on user behaviour, service decisions, utilisation rates, market alternatives and logistical convenience. Return volumes are influenced by installed base, ownership of the core, return incentives and competition for used components. Quality varies because products return at different lifecycle stages and under differing operational conditions. These uncertainties directly affect planning, inventory, yield and profitability.

Acquisition control can be strengthened through deposits, buy-back prices and other return incentives. Sorting and grading cores into quality classes improves production planning and pricing logic. Forecasting is essential because remanufacturers need to anticipate not only how many products may return but also in what condition they are likely to return. Earlier-stage product recovery may be particularly profitable, underscoring the value of timely intervention. [18], [19], [20]

Return strategies such as deposits, leasing models, customer-owned returns and trade-ins can reduce uncertainty, but they require suitable reverse-channel design. Dealer networks, third-party collection models and platforms that improve information exchange on core supply and demand are identified as relevant enablers. Relationship type and logistical convenience are identified as critical factors for successful core acquisition. [18], [19] Successful remanufacturing system requires well-established reverse logistics and returns loops. The current logistics systems between manufacturer and user not yet fully support reverse logistics as they are still more driven by conventional distribution logistics [11].

The same challenge area also creates business opportunities. Deposit optimisation can improve yields of strategically important cores. Standardised inspection can reduce disputes over refund levels and improve process transparency. Marketing remains essential for building customer trust in remanufacturing as a credible lifecycle option. There are also important links to service models, product-as-a-service concepts, leasing arrangements and data-driven offerings that improve visibility into the installed base and help create more predictable return flows.

3 Legislation and standards

3.1 Regulatory environment

The European regulatory framework is becoming increasingly relevant for remanufacturing. The Ecodesign for Sustainable Products Regulation, Regulation (EU) 2024/1781, strengthens policy expectations regarding product durability, repairability and lifecycle transparency. It also introduces the Digital Product Passport (DPP) as a key mechanism for traceability and information access. The expected implementation pathways associated with the DPP are presented in Table 1 [21]. These developments are directly relevant for remanufacturing because they support longer product life and better lifecycle visibility, both of which are foundational to industrial recovery and second-life strategies [22].

Table 1. The implementation pathways associated with the DPP [21]

Item	Implementation timeline
Batteries for industrial and electric-vehicle applications	2027 through the Battery Regulation
Tyres	2027 – 2029
Iron and steel	2026 – 2028
Aluminium	2027 – 2030
ICT / Electronics	2026 – 2027
Electric motors and variable speed drives	2026 – 2027

Additional policy instruments reinforce the same direction. The Circular Economy Action Plan (CEAP) supports lifecycle-oriented product policy, including relevance for batteries and vehicles and for electronics and information and communication technology (ICT)[23]. The anticipated Circular Economy Act (CEA) is likely to strengthen remanufacturing, refurbishment and repair through common standards and reduced barriers linked to secondary raw materials [23]. The Right to Repair Directive, Directive (EU) 2024/1799, is currently consumer focused, but it strengthens the wider policy principle that repair information and product openness should support longer use phases [24].

The EU Machinery Regulation, Regulation (EU) 2023/1230, introduces an additional layer of relevance for remanufacturing in machinery-intensive sectors. Applicable from January 2027, it updates safety and compliance expectations for digital, connected and AI-enabled machinery, including issues linked to cybersecurity, software, documentation, conformity assessment and substantial modification. This is highly relevant where remanufactured machinery incorporates updates or changes affecting compliance status, because remanufacturing activity may then intersect directly with safety obligations and technical documentation requirements [25], [26].

3.2 Standards and quality assurance

Formal standards are increasingly important in building credibility and consistency in remanufacturing. ANSI/RIC001.2-2021 is identified as a major benchmark for remanufacturing process control and quality assurance [27]. Although voluntary and developed in the United States, it provides a useful point of reference for demonstrating that remanufacturing processes are controlled, repeatable and aligned with recognised quality expectations.

The emerging ISO 59000 family strengthens the connection between remanufacturing and the broader circular economy standardisation agenda: ISO 59004 on terminology, principles and guidance for implementation; ISO 59010 on business models and value networks; ISO 59020 on measuring and assessing circularity; ISO 59040 on product circularity data sheets; and ISO 59014 on principles, sustainability and traceability requirements for secondary materials recovery. Taken together, these standards help establish a more consistent language and measurement basis for circular industrial practices [28].

Additional standards of relevance include ISO 8887-1:2017 and ISO 8887-2:2023 relating to technical product documentation and design for manufacture, assembly, disassembly and end-of-life. ISO 9001 and ISO 14001 remain important general references for quality and environmental management. Sector-specific standards, including automotive-oriented requirements and machinery-specific technical standards, complement this framework. For example, ISO 10987-2:2017 Earth-moving machinery — Sustainability Part 2: Remanufacturing, gives requirements for identification and labelling, applicable processes, and relevant information for remanufactured components for earth-moving machinery. The overall conclusion is that the standardisation environment is becoming more supportive of remanufacturing through a combination of process standards, data standards and management standards rather than through any single all-encompassing framework.

4 Remanufacturing reference cases

4.1 Industrial reman programmes

Large OEMs have developed remanufacturing programmes that show how circular value creation can be integrated into global service, parts and lifecycle businesses. These programmes are not limited to workshop-level refurbishment, and they combine installed-base access, dealer and service networks, return incentives, standardised industrial processes, quality assurance and customer-facing value propositions. In this context, remanufacturing becomes a structured business capability that supports availability of high-value components, reduces lifecycle cost for customers and preserves material value within the OEM ecosystem.

The programmes of companies such as Caterpillar[29], Liebherr[30], Komatsu[31], John Deere[32], AGCO[33], CNH[34] and Volvo[35] illustrate different levels of maturity and strategic emphasis in industrial remanufacturing. Cat Reman represents a highly scaled global programme with thousands of remanufactured options, extensive distribution coverage and a strong role for dealer-based core returns and exchange models. Liebherr and Komatsu show how remanufacturing can be embedded into heavy equipment and mining service operations, where expensive components, long machine lifetimes and uptime requirements make controlled component recovery particularly valuable. John Deere, AGCO, CNH and Volvo further demonstrate that remanufacturing is becoming a normalised part of off-highway, agricultural and construction equipment service portfolios, often linked to fast replacement, cost predictability, warranty-backed quality and circularity objectives.

Table 2 summarize how the programs differ in their treatment of core predictability, condition assessment, deposit and core-credit mechanisms, and business-model emphasis. Some programmes rely on exchange-based models that support predictable returns, while others use more permissive acceptance criteria to increase return rates. Condition assessment ranges from field-based valuation to full teardown and original-equipment-level testing. Deposit structures vary between fixed exchange credits and condition-based refunds. Business-model positioning also differs, with some programmes emphasising uptime and cost predictability and others presenting remanufacturing as a key element of circularity or total-cost-of-ownership strategy. These differences indicate that successful remanufacturing models remain closely tied to installed-base structure, product architecture, channel control and service strategy.

Table 2. Examples of leading OEM remanufacturing programmes by core predictability, condition assessment, deposit systems and business-model emphasis

Company	Core predictability	Condition assessment	Deposit / core credit	Business model
Caterpillar	- Core return is part of the sale - **Predictability is based on the dealer network and a broad OEM installed base** - Recommendation for preventive replacement before failure	- **Multi-stage evaluation (complete / damage / usability)** - Core is inspected before acceptance - Full teardown + OEM-level testing	- Deposit is included in the product price - **Credit based on condition:** full / partial / no credit - Credit can be used at purchase or later	- Integrated OEM business - High margin business (reman often more profitable than new) - Goal: maximize material value over the lifecycle (customer relationships, extend lifecycles, manage material flows)
Liebherr	- Exchange model is based on the known component return - Core return tied to component exchange - **Fixed return criteria** lead to higher predictability	- Full teardown, cleaning and OEM testing - Only OEM components	- **Fixed credit** value for approved core - Clear programs (Repair, Fixed Price and Cost Cap Exchange) - Predictable cost structure for the customer	- Integrated into service business - Focus: **uptime + cost predictability** - Multiple service levels
Komatsu	- **More permissive acceptance** enables better return rate	- Fast visual field assessment “on-the-spot assessment and valuation” - Full OEM testing at the factory - Condition monitoring in use (Komtrax)	- **Generous core credit** - Credit tied to exchange	- Reman as a part of Total Cost of Ownership (TCO) strategy - Focus: **lower operating cost and fast availability** - Volume-based efficiency
John Deere	- No specific information available	- **3-level credit (100% / 50% / 0%)** - Mechanical and visual criteria	- Credit only for approved core - **Strict return conditions (time, condition)**	- Increased uptime with a fast, low-cost repair option
AGCO	- “One-in one-out” logic - Service appointment booking	- Full teardown, documentation and testing	- Deposit at purchase (~50% of price), refunded when core is returned	- Lifecycle service especially for older equipment - Short downtime - Focus: **speed + cost savings**
CNH (e.g. New Holland)	- Dealer-driven	- Values vary with condition	- Deposit based on condition - **Core buy back campaigns**	- Long warranties (e.g., 24 months) - Data- and process-driven business
Volvo	- Tied to the circular business model - OEM controls the lifecycle	- Full teardown + OEM updates - High reuse rate (materials) - Components often upgraded	- Deposit included in the product price - Credit based on condition	- **Circularity strategy** (reman is a key part) - Focus: maximizing resource utilization

4.2 Customer value proposition and adjacent digital service opportunities

Remanufacturing offerings are presented through a value proposition that combines economic, operational, and environmental benefits. Companies in the analysed cases report cost savings of approximately 45 to 85 % compared to purchasing a new equivalent product. They also emphasise a lower total cost of ownership. In addition, remanufactured products typically lead to shorter downtime compared to extensive repair solutions. They are expected to deliver original equipment quality and performance. Warranty periods usually range from 12 to 24 months, which further increases customer confidence. Environmental benefits are also highlighted, particularly reduced energy consumption and lower material use. Overall, these value propositions address the main customer concerns in remanufacturing markets, namely cost, reliability, and risk.

Adjacent service opportunities are increasingly data driven. In this case tyre monitoring and operations-management solutions such as Bridgestone iTrack [36], Kal Tire TOMS [37] and Goodyear [38] heavy-duty monitoring systems. These solutions provide real-time information on temperature, pressure, damage, maintenance history, tread depth and machine operating hours. While these examples are associated with tyres and retreading rather than conventional component remanufacturing, they illustrate how condition monitoring and connected services create the information basis needed for more effective lifecycle management.

As an example, Michelin's TreadVision and Smart Predictive Tire solution, reported in March 2026, report their pilot where fewer emergency roadside tyre events, longer tyre life when under-inflation was corrected, and lower fuel consumption when recommended pressures were maintained [39]. The broader relevance lies in demonstrating how digital inspection, predictive analytics and platform-based fleet insights can support circular service models by improving intervention timing, reducing avoidable failure and preserving component value for subsequent reuse or retread pathways [40].

5 Factors for business growth (PESTEL)

The factors for business growth for remanufacturing are identified with PESTEL framework. The framework includes perspectives from political, economic, social, technological, ecological and legal factors. The factors are identified based on the previous analysis and findings related to the key themes. The PESTEL framework examines factors on different timespans – near future during the project (0 - 2 years), after the project (2 - 5 years) and in a long-term (5 - 10 years). The listed factors are divided between enablers and barriers. The PESTEL analysis is conducted mainly in a European context but considers also the global trends and standards.

5.1 Political

Public support accelerates the implementation of remanufacturing and guides towards AI-driven solution. There are multiple political factors related to the growing remanufacturing markets assisted by AI. Political factors are mainly guiding towards remanufacturing practices and accelerates the market growth, but there are also some factors that creates uncertainty and still needs development. Political factors reshape the broader landscape of the field and affects how the markets are forming. One main guiding aspect is the incentive towards material circulation whether it is driven by general circular economy and sustainability or saving resources of different possibly even critical raw materials. Other aspect shaping the remanufacturing is the public funding and investments to the technologies and innovations on the field. It affects what actions are taken and to which direction the development is heading. Prioritising remanufacturing can be viewed as a political aspect. The scope of the policies is still unclear. There is uneven implementation of the policies due to geographic distribution and global division of competencies and expertise.

5.2 Economic

Economic factors affecting the remanufacturing are related to the costs and maintaining the business. As already discussed, the markets of remanufactured products are shaped by the price of the remanufactured product or component. The production costs of remanufactured component are less from material perspective as it doesn't require as much extracting new raw material. Due to technical AI-driven solutions, the manufacturing costs of remanufactured components and the overall process efficiency can create cost savings. However, the transition towards more remanufactured components can modify the market prices for certain raw materials or energy. There can also be adverse economic effects or consequences. If the business model is highly tied to the core and their yield, there can occur a lot of variation with the revenues. It can also affect whether it is part of the business model to provide reward for the customer for returning the core to remanufacturing. Depend also how the logistics and reverse supply is organised, but it may cause new costs for the manufacturer.

Remanufacturing enables the creation of new kinds of business models that are focused on around the R-strategies[1] activities. It also provides opportunities for manufacturers to extend their business beyond traditional manufacturing. Remanufacturing services could also be offered by other than OEMs, which can cause complexities or tensions. Scaling remanufacturing business also improves local or national supply chain and production resilience as manufacturing is not dependent on OEMs.

5.3 Social

The social factors affecting the market growth of remanufacturing are mainly related to workforce and social sustainability. The dependencies from virgin raw materials, especially metals are less when the components are remanufactured. That affects positively to the social sustainability as traditionally the metal mining especially outside of EU has adverse effects on the local social sustainability. One social aspect is how the remanufactured parts are perceived. Perception of remanufactured products can vary depending on the component type and use. Especially for components with long lifespan, which are used inside a machine, the lower price and more ecologically friendly option might seem appealing.

Other aspect is the workforce and skill shift that takes place when the manufacturer starts to remanufacture products. More special knowledge is needed when the products are remanufactured as the remanufacturing depends on the product quality, use history and complexity. The traditional manufacturing jobs might be replaced by more digitalised works such as robotics and the use of AI, but remanufacturing creates new kind of

[1] The R-strategies, structured as a 10-step hierarchy (R0 to R9), prioritise sustainability by aiming to prevent waste generation, extend product lifespans and maximise material efficiency [41]

demand for skilled workforce. A skill shift can also create skill shortages to specific skills and knowledge, and it might be difficult to predict what type of skills are needed especially in the developing AI environment. AI development can also replace other workforce in addition to the traditional manufacturing jobs replaced by digitalisation and robotics. There are also questions about the ethics of AI-driven decision-making as the algorithms can make biased decisions when human is not involved [17].

5.4 Technological

Discrete manufacturing requires technological maturity, specialised skills and product-specific knowledge to address the different requirements of remanufacturing. Remanufacturing is enabled by advances in manufacturing process technologies as well as data-level capabilities. Processes become more efficient when digital technologies and digital twins support data transfer throughout the product lifecycle. The rapid development of AI can further accelerate these improvements.

AI-driven technologies or other digital solutions can occur at different stages of the remanufacturing process. Multiple possible digital solutions can be implemented throughout the product lifecycle and therefore also during the remanufacturing stage. Data is in a key position during the process, and it can be shared through platforms or other network-like solutions, creating a digital twin of the product or with a DPP.

Before the actual manufacturing of the component, AI-assisted estimation of remaining useful lifetime [17] can be used to estimate how long the product will be in use. The data from it can also be used to estimate the core yield. When the core arrives to the remanufacturing plant, AI can be used for condition monitoring and inspection. However, varying core condition can be a challenge for implementation of this practise. Robotics, AI and machine learning can be used for disassembly and quality control of the remanufactured component. Depending on the product or a component, the electronics complexity can make the process more difficult and prevent the efficient use of machine learning or AI in the inspection.

5.5 Ecological

Ecological factors affecting remanufacturing are mainly linked to circular economy principles: eliminating waste through eco-design, circulating products and materials, and restoring resources. Remanufacturing is one of the circular economy R-strategies, alongside related approaches such as refurbishment and repair. It supports positive environmental impacts by reducing the need for virgin raw materials, using existing cores and materials, and decreasing waste compared with recycling or disposal. However, measuring these environmental benefits remains challenging because of data gaps and limited knowledge of broader system-level impacts. AI-driven solutions can help address this challenge by improving lifecycle data collection, supporting environmental impact assessment, and identifying when remanufacturing, repair or recycling provides the most resource-efficient option. In this way, AI can guide environmental decision-making, strengthen the verification of circularity benefits, and align remanufacturing actions with company-specific sustainability goals.

5.6 Legal

Legal factors are drivers for the implementation and forces manufacturers and related companies to adapt different regulation and standardisation. They can affect the remanufacturing scheme by guiding towards scalability of remanufacturing and wider adoption. Regulation and standardisation can also affect the quality or other requirements of remanufactured components, such as product safety compliance. Regulation could force to prioritise remanufacturing beyond the political incentives. Standards are efficient way to unify the operations.

Remanufacturing and product traceability requires a lot of data and there can be different regulatory aspects related to the data governance and data management, e.g., who has access to which data. Also, different property regulations can occur related to the physical core ownership and its circulation. Depending on the product type there can also be legal factors regarding OEMs' components, which affects the third-party manufacturers and market dynamics.

5.7 Enables and barriers for business growth

Remanufacturing markets are expected to grow, but their expansion depends on multiple factors identified in the PESTEL analysis. The findings are summarised in Table 3. The report shows that artificial intelligence, data sharing, and traceability can play a central role in improving forecasting, inspection, estimation of remaining useful life span and overall process efficiency. It also shows those political, economic, ecological, and legal drivers such as circular economy policies, cost savings and reduced circulating material use shape the market context.

Across all three timeframes, the main enablers for business growth in remanufacturing are strengthening policy support, clear environmental value and improving digital and traceability capabilities. The most persistent barriers are uncertain core returns, consumer trust gaps, high reverse-logistics and compliance costs, and the fact that remanufacturing still sits inside a complex multi-regulation environment rather than under one clear legal framework.

Table 3. Identified Enablers and barriers for business growth (PESTEL)

	Near future (0 - 2 years)	Mid-term (2 - 5 years)	Long-term (5 - 10 years)
Political	**Enablers:** EU circular economy policies (e.g. ESPR, CEAP) supporting durability and lifecycle extension **Barriers:** Policy scope uncertainty and fragmented implementation	**Enablers:** Stronger policy incentives and public funding for remanufacturing and AI-enabled solutions **Barriers:** Uneven implementation across regions and industries. Need for strong compliance resources.	**Enablers:** Policy-driven prioritisation of remanufacturing as a core industrial capability **Barriers:** Global misalignment of policy frameworks
Economic	**Enablers:** Lower material costs and reduced dependency on virgin resources. More price-sensitive customer groups and additional after-sales revenue. **Barriers:** High reverse logistics and core acquisition costs. High initial investments.	**Enablers:** New business models (e.g. buy-back, leasing, product-as-a-service) improving value capture **Barriers:** Revenue variability due to uncertain core supply and quality	**Enablers:** Stable service-based revenue models and lifecycle value optimisation **Barriers:** Competitive tensions between OEMs and third-party remanufacturers
Social	**Enablers:** Creation of local jobs and increased affordability of remanufactured products **Barriers:** Limited awareness and trust in remanufactured products	**Enablers:** Improved social sustainability through reduced reliance on raw material extraction **Barriers:** Core ownership conflicts and changing workforce requirements	**Enablers:** Increased customer acceptance and trust in remanufactured products **Barriers:** Skills shortages in AI, data, and remanufacturing expertise
Technological	**Enablers:** AI-assisted inspection, condition monitoring, and predictive maintenance **Barriers:** Variable core condition and limited data availability	**Enablers:** Increased technological maturity, digital twins, and traceability (e.g. DPP) **Barriers:** Increasing electronics and software complexity limiting remanufacturing	**Enablers:** Design-for-remanufacturing and integration of software-enabled components **Barriers:** Dependence on proprietary software and restricted data access
Ecological	**Enablers:** Reduced raw material use, emissions and energy consumption **Barriers:** Data gaps in lifecycle environmental impact assessment	**Enablers:** Reduced waste through extended product lifecycles **Barriers:** Lack of standardised methods for system-level impact measurement	**Enablers:** System-level resource efficiency and circularity normalised **Barriers:** Difficulty verifying circularity benefits at scale
Legal	**Enablers:** Increased traceability (e.g. DPP) and sustainability requirements **Barriers:** Warranty, liability, and compliance risks (especially for reman products)	**Enablers:** Development of data governance and standardisation frameworks (ISO, CEAP) **Barriers:** Increasing safety and compliance requirements (e.g. Machinery Regulation)	**Enablers:** Harmonised regulatory framework enabling scalable remanufacturing markets **Barriers:** Intellectual property and data ownership constraints limiting market access

6 Summary

The reviewed material for this deliverable indicates that future remanufacturing growth is likely to arise where several enabling conditions reinforce one another. These include designs that support disassembly, inspection and upgrading, access to reliable lifecycle data, predictable reverse logistics, robust condition assessment, quality assurance frameworks, and business models that maintain connection to the installed base. In off-highway and forestry-related contexts, the economic and environmental rationale can be particularly strong because component values are high and products have long service lifetimes, although operational complexity is correspondingly greater.

The assessment highlights the importance of data-enabled lifecycle value creation. Remanufacturing is evolving beyond the restoration of function towards the optimisation of maintenance timing, product recovery, component reuse and information-driven decision-making. These puts increasing emphasis on digital connectivity, traceability, service-system design and business models capable of coordinating product, data and return flows.

The regulatory trajectory in Europe further strengthens this direction. Legislative developments linked to durability, repairability, traceability, machinery safety and product information are increasing both the opportunity and the governance requirements for remanufacturing. Rather than acting solely as compliance obligations, these developments can also serve as enabling conditions for industrially credible and scalable remanufacturing systems when firms are able to integrate them into design, service and value-chain management.

In conclusion, remanufacturing is emerging as a strategic industrial capability at the intersection of circular economy policy, digitalisation and service-based value creation. The strongest market opportunities are likely to arise where firms combine technical remanufacturing competence with systematic lifecycle information, customer access, reverse logistics and credible quality assurance. This makes remanufacturing not simply an aftersales activity, but an increasingly central element of future competitive and sustainable industrial systems.

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