MASTT2040 Industry Action Plan

Funded by the European Union

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Contents

1 Executive Summary

This document presents an Industrial Strategy and Action Plan to maximise future Manufacturing-as-a-Service (MaaS) utilisation for the benefit of the EU industry. This takes into account current trends in manufacturing and opportunities for Manufacturing-as-a-Service. How these opportunities can be maximised is further explored and barriers to implementation, such as data standardisation, are considered. Finally, recommendations on how these barriers can be addressed, e.g. via standardisation, policy, strategic investment, are put forward with identification of high impact priority actions in the short, medium and long terms. The aim of this Industrial Strategy and Action Plan is to stimulate and speed up uptake of MaaS in European industry and inform future EU funding programmes, EDIHs, Public Private Partnerships and other initiatives. The work has been performed as part of the EC funded MASTT2040 (Manufacturing as a Service for the EU's Twin Transition until 2040) strategic foresight project[1]. MASTT2040 has been building an understanding of the industry changes, opportunities or disruptions emerging both inside and outside of the "Manufacturing as a Service" (MaaS) domain to guide decision making, strategies and actions for the EU manufacturing sector in the context of twin transition up to 2040. MaaS promises a unique value proposition compared to the existing traditional centralised manufacturing approaches by offering increased flexibility and resilience, and scale-up driven by rapid advances in connectivity, digitisation, data analysis and exploitation of AI. This supports key goals of the EC with respect to strategic autonomy, resilient supply chains and sustainable and circular practices to reduce reliance on critical raw materials.

2 Introduction

We are currently at the start of two major, complementary transitions driven by digitalisation and by the need to be more sustainable. Already these two transitions are having major impacts on the European manufacturing industry driving more digitised industrial production and leading to new models such as Manufacturing-as-a-Service. At the same time the move towards more climate neutral, circular and digitised industrial production is radically changing how manufacturers produce products. These fundamental changes are challenging existing linear models based on centralised manufacturing approaches. As a result of this the MASTT2040 project has been investigating how distributed MaaS approaches can be exploited by industry to provide more flexible, resilient and efficient manufacturing of products while also considering how industry can embrace the Circular Economy to create a more sustainable future.

The report first discusses the trends that are driving manufacturing industry and highlights key concerns and new priorities that have arisen due to recent geopolitical changes. The potential impact of MaaS with respect to providing more flexible manufacturing, resilient supply chains, sustainable and circular supply chains and the implications for future workers are discussed. This leads to a vision for MaaS in 2040 and a roadmap of activities in the short, medium and long terms. Key is maximising impact for European Industry and this is addressed through identification of enablers and barriers to success. Finally, high impact tangible actions and recommendations are put forward for industry, policy makers, researchers and standardisation bodies along with a cost table of investments required.

[1] https://www.mastt2040.eu/

3 What is Manufacturing-as-a-Service?

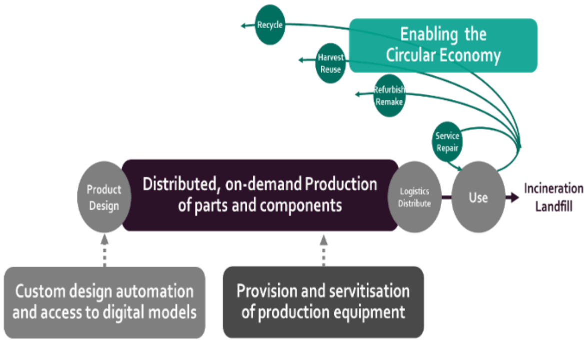


Figure 1. Manufacturing as a Service Models and Linkage to the Circular Economy

Increased digitisation is leading to new business models and many companies now exploit software-as-a-service (SaaS) models as well as accessing processing resources via cloud computing. Manufacturing as a Service (MaaS) adopts a similar business model but for manufacturing allowing companies to access distributed manufacturing resources and expertise.

> ***Manufacturing as a Service***
> ***is a distributed system of production in which resources (including data and software) are offered as services, allowing manufacturers to access distributed providers to implement their manufacturing processes[2].***
>
> ***EC Definition***

MaaS is particularly beneficial for companies that do not have the internal resources to produce something in-house or for companies that need to scale up quickly to meet an order giving greater flexibility and responsiveness to production demands. In practice a number of different MaaS models can be used for on-demand manufacturing of products as a service as shown in Figure 1. These are:

- **Distributed on-demand manufacturing of parts and components** through manufacturing platforms and digital services, provides SMEs and large enterprises seamless online access to distributed manufacturing capabilities. This enables the on-demand manufacturing of custom parts and components with high flexibility and short lead time.
- **Custom design automation and access to digital models,** generating or providing access to all digital product data (digital twins) enabling the distributed on-demand manufacturing of parts and components.
- **Provision and servitisation of production equipment,** termed "Equipment as a Service," offering flexible access to equipment, infrastructure, or production facilities, along with cloud platforms and digitised services that remotely optimise their operation.

In practice, companies might combine different service models in their service offering. In addition to these core models corporate sustainability is now a driving topic for industry, and this is promoting a move towards a Circular Economy and R-cycles. R-cycles refer to "inner circles of the circular economy" aimed at reducing waste and supporting value retention strategies for the resources by focusing on reusing, repairing, refurbishing, reconditioning and remanufacturing products. These R-cycles can be enabled through platforms, digital product passports and digitised services enhancing sustainability and supporting a product's more circular lifecycle. The key features of MaaS business models are:

- Exploitation of real-time, easy to use, instant cloud services employing learning algorithms that can provide instant quoting.
- Provision of short lead-times via highly digitised and automated processes enabling "micro-caring of customer needs".
- The provision of cost-effective hyper-scaling of the service with limited need for human resources.
- The integration of in-depth manufacturing knowledge in the digitised services reducing the need for highly skilled workers.

[2] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl4-2024-twin-transition-01-03

4 World Trends in Manufacturing and Industry Drivers

A number of key trends are driving manufacturing leading to more interest in MaaS business models. These include digitisation at all levels, the exploitation of robotics and automation, an explosion in the use of AI, increased adoption of servitisation business models and growing awareness of the need for resilience to geopolitical tensions as well as sustainability and decarbonisation of manufacturing processes. A number of factors have given impetus to digitalisation within the industry including the digitalisation of society in general, the increasing use of AI in everyday life and the impact of the COVID crisis in 2019 that highlighted the benefits of digitalisation.

> ***"We have vaulted five years forward in consumer and business digital adoption in a matter of around eight weeks."[3]***

4.1 Digitalisation

Digitalisation is enabling manufacturers to optimise processes, improve quality and reduce costs. The increased use of the Internet of Things, Artificial Intelligence and cloud computing in manufacturing is revolutionising manufacturing processes. This is being driven by initiatives such as Industry 4.0 which has the aim of enabling the real-time data collection and analysis of vast amounts of data to provide valuable insights into manufacturing operations. Via increased exploitation of data organisations can more easily manage and maintain equipment, collect and store key data in local or global clouds and use communication to integrate equipment creating more flexible, agile manufacturing systems that can adapt quickly to changes in demand. Going beyond this MaaS extensively exploits automation of office processes, making information seamlessly available through the entire production process, from the order to the production and delivery.

4.2 Robotics and Automation

Increased use of robotics and automation has been a trend since the 1970s and has transformed many manufacturing sectors. This trend is expected to continue with flexible robotic process automation, collaborative robotics and fully automated "lights out" factories driving future smart manufacturing. Robots can perform repetitive tasks faster and with a much higher degree of accuracy and precision than human workers, improving product quality and reducing defects. Robots will become increasingly integrated with Industrial Internet of Things (IIoT) sensors and big data analytics to create more flexible and responsive production environments. Increased automation has major impacts on system efficiency, error reduction, equipment downtime and worker safety. If a manufacturing process is highly automated, it can also operate 24/7 significantly increasing productivity.

4.3 Artificial Intelligence (AI)

Increased digitisation and connectivity provided by the Industrial Internet of Things (IIoT) allows devices and sensors to collect valuable data from machines, equipment and production lines. Via the exploitation of AI algorithms manufacturers can quickly process and analyse vast amounts of data in real time to identify patterns and trends, giving a much greater understanding of how production processes are performing. Machine learning algorithms are being increasingly used to a identify patterns in the data and manage decision-making based on those patterns, allowing manufacturers to catch quality issues early in the production process and optimise processes. Companies can also use AI to identify anomalies and equipment defects quickly to reduce equipment downtime and outages as well as to predict failures in machinery based on trends. Looking to the future AI is expected to impact all aspects of manufacturing.

[3] McKinsey, The COVID-19 recovery will be digital: A plan for the first 90 days, 5/14/2020

4.4 Servitisation

Servitisation is a business model that is increasingly being used in areas such as maintenance, repair, upgrades and now in Manufacturing-as-a-Service companies. In servitisation rather than selling a product a service is provided, and this changes the dynamic with the customer building stronger relationships, increasing customer loyalty and generating recurring revenue streams. In return manufacturers can gain valuable insights into their customers' needs and preferences, which can inform product development and improve customer satisfaction. By providing servitised offerings manufacturers can differentiate themselves from competitors by offering value-added services that enhance the customer experience. This has led to the growth of MaaS business models. A good example of servitisation is additive manufacturing or 3D printing which is changing the way companies design, prototype and manufacture products. 3D printing is a popular tool for producing complex parts and components quickly and precisely as manufacturers can produce complex geometries in a single step, reducing manufacturing time and costs. It can also be used to produce spare parts on-demand reducing the need for large inventories. Going forward Manufacturing-as-a-Service approaches are likely to radically change the manufacturing landscape.

4.5 Sustainable Manufacturing and Decarbonisation

Within Europe there has been growing prioritisation of the "Green Transition" with the aim of making Europe Climate Neutral by 2050 through the Green Deal[4]. Consumers are becoming more environmentally conscious, and this awareness is increasing. This is leading to new regulations and demands on companies, e.g. Corporate Sustainability Reporting[5], to reduce carbon emissions and protect the environment. Manufacturers are under pressure to mitigate the impacts of climate change by minimising their carbon footprints with the aim of achieving carbon neutrality. This is a challenge as manufacturing processes often require large amounts of energy, water, raw materials, chemicals (in many cases toxic) and produce harmful waste as well as other by-products. There is a growing push to achieve sustainable manufacturing to reduce waste, conserve resources (particularly critical raw materials) and minimise the use of harmful substances. This is leading to manufacturers increasingly adopting renewable energy sources, reducing use of raw materials, employing circular economy approaches and implementing eco-friendly production processes.

4.6 Additional Driving Trends Identified by MASTT2040

In addition to the overall trends in manufacturing the MASTT2040 project interviewed industry and performed a Delphi study to capture Industry's current drivers. As well as increasing availability of automation and the abilities of automated production systems increasing speed of evolution of Artificial Intelligence (AI) is seen as a key driver. Digital transformation of the manufacturing sector is occuring rapdily including the increasing use of smart data and digital twins in production. It was also noted that there was a move towards platformisation of economic activity, including servitisation of manufacturing as well as a move to localisation of the manufacturing and remanufacturing cycle, including increased tailoring of manufacturing services to local demand and regulation. This is leading to growing cooperation between industry stakeholders in manufacturing clusters. Some challenges were also identified such as the growing cybersecurity challenge, the increase in regulations impacting business activities in Europe and growing competition from China's innovation capabilities as well as a growing influx of competitively priced products from China. The rising environmental consciousness and its growing impact on manufacturing regulations was also noted. Three

[4] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[5] https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

trends were consistently rated as highly influential for the future of manufacturing (whether for MaaS or not). These were:

- Increasing availability of automation and the abilities of automated production systems.
- Digital transformation of the manufacturing sector.
- Increasing speed of evolution of Artificial Intelligence (AI).

Some trends were considered less influential at present:

- Rising environmental consciousness and its growing impact on manufacturing.
- Growing prices of energy.

The influence of 19 key identified trends on Centralised, Contract and MaaS manufacturing business models was also explored as shown in Figure 2[6].

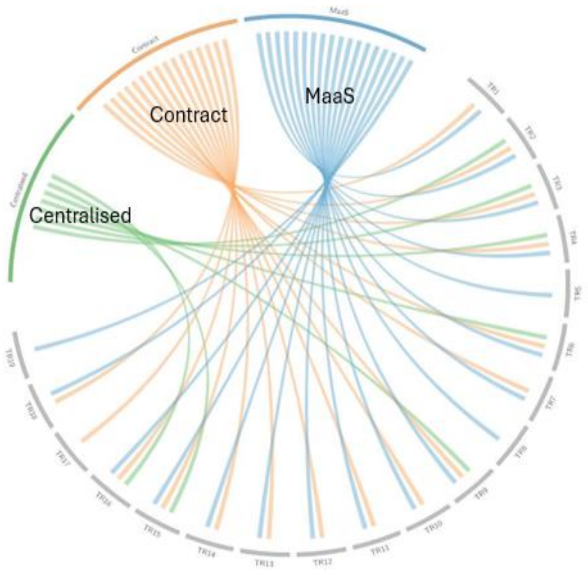


Figure 2. Mapping of Trends to Centralised, Contract and MaaS Business Models

• Centralised Manufacturing is a manufacturing approach where all manufacturing activities are concentrated in a single location or a few strategically chosen locations.
• In Contract Manufacturing production is outsourced. MaaS is a specific form of Contract Manufacturing which relies on a high level of digitalisation, automation and decentralisation utilising multiple suppliers and locations.

A combination of Centralised Manufacturing, Contract and MaaS Manufacturing can be used for the manufacturing of parts/components in a supply chain, but it stops being centralised if most of the manufacturing process is being outsourced to third parties.

The assessment of trends highlighted that Centralised manufacturing may benefit significantly from automation, AI, and digitalisation, but may face challenges due to rising labour costs in Europe and potential disruptions in the supply of critical materials. Contract manufacturing could also thrive with the adoption of automation, AI, and digital technologies, and can further benefit from increased interconnectivity and collaboration between industry stakeholders.

Manufacturing-as-a-Service, however, has the potential to be the most adaptable model, benefiting from resilience to supply chain disruptions, exploitation of localisation and personalisation, and better immunity to the rising demand for skilled tech-savvy labour. Its success will rely heavily on digital transformation, automation, and interconnectivity. A number of trends were also noted that are specifically driving MaaS:

- Growing interruptions to supply of critical minerals, materials and products.
- Localisation of manufacturing and remanufacturing cycle, featuring increased customisation of manufacturing services to meet local demand & regulations.
- Growing demand for personalised products.
- Increasing interconnectivity between companies thanks to the IIoT.
- Growing cooperation between industry stakeholders (manufacturing clusters).
- Rapid development of additive manufacturing technologies and 3D printing technologies.

[6] https://www.mastt2040.eu/2025/02/17/mastt2040-d2-1-future-of-maas-in-europe-the-2040-vision-trends-scenarios-and-use-cases/

4.7 A New World Order- Technological Sovereignty and Resilience of Supply Chains

As highlighted in the Draghy Report[7] Europe is facing a key challenge for the future. A slowdown in productivity growth in Europe has led to a wide GDP gap between the EU and the US. As a result, the living standards for European households has gone down while US households have nearly doubled their disposable income since 2000. European companies are facing greater competition from abroad, reduced access to overseas markets increasing energy costs due to geopolitical tensions and vulnerabilities in the supply of critical materials. Although Europe is very strong in research and innovation it struggles to compete due to a number of structural disadvantages such as higher labour costs because of a good welfare system, higher energy costs due to the need to import energy at a higher price, and reliance on critical raw materials from other countries. Most activities to try and encourage competition are also performed at a national level leading to a fragmented and uncoordinated response against large competing countries.

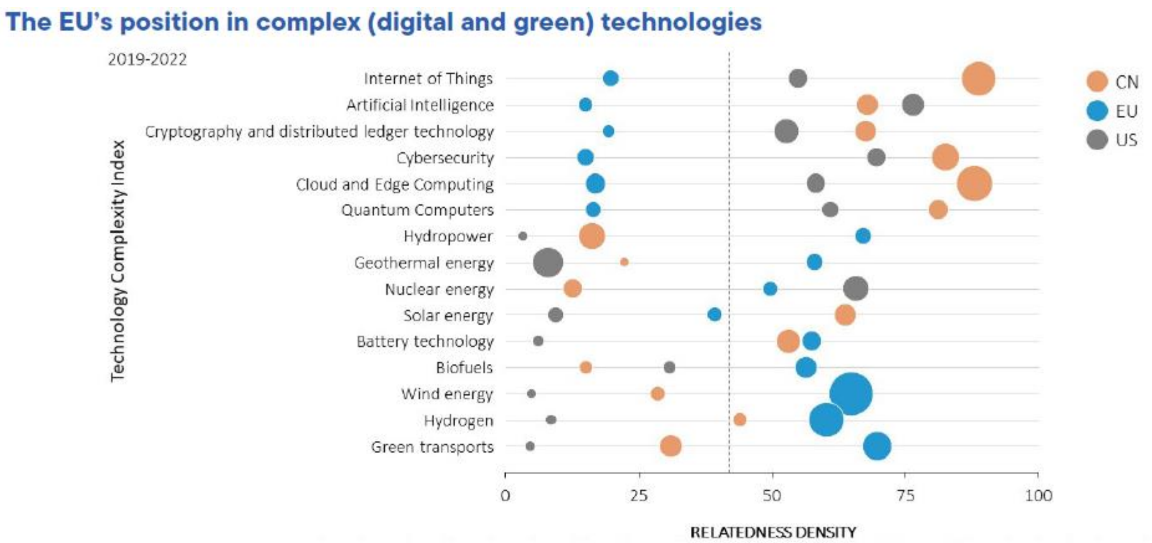
Research by DG RTD shows that Europe is behind in its adoption of the digital revolution and needs to strengthen its position and focus its collective efforts on the emerging technologies that will drive future growth to close the innovation gap with the US and China. By 2040, the workforce is also projected to shrink by close to 2 million workers each year[8] placing greater empahasis on productivity. Demographics indicate that, while the labour force in Europe will shrink, the US population is projected to expand in the coming decades. Significant investment is required to digitalise and decarbonise the economy as well as increase European defence capacity. Notably Europe has not been successful in setting up large companies in the last 50 years (i.e. companies with market capitalisation over EUR 100 billion) while the US has created six companies with a valuation above EUR 1 trillion. This can be explained by a European concentration on improving mature technologies with limited breakthrough potential and lack of investment for tech industries. Notably over the past 20 years automotive companies have been the top 3 investors in European R&I while in the US this has shifted from automotive and pharma companies in the early 2000s to tech companies today. In particular, Europe is falling behind in translating innovation into commercialisation, and innovative companies struggle to scale due to lack of investment. They are also hindered by inconsistent and restrictive regulations. Notably many European entrepreneurs seek financing from US venture capitalists and between 2008 and 2021 30% of the "unicorns" founded in Europe relocated their headquarters abroad, with the vast majority moving to the US[9].

4.7.1 Productivity

Fundamental changes are required, and Europe must digitalise and embrace the use of AI to improve productivity. Much of successful digitalisation is due to human acceptance and Europeans will need the appropriate skills to benefit from the technologies in a socially inclusive manner providing opportunities for education and adult reskilling to provide rewarding jobs.

The MaaS platform landscape is currently dominated by non-EU players, particularly from the United States which are expanding their reach into Europe through acquisitions. European MaaS platforms often face challenges in scaling and competing with their US counterparts, primarily due to differences in investment levels, market reach and technological infrastructure. Strategic investments and collaborations are thus needed to enhance Europe's position and avoid foreign dominance.

[7] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[8] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[9] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en



Notes: The results are based on an analysis of patent data to understand the complexity and potential for specialisation in different technology areas. On the y-axis, technologies are ranked according to how advanced or complex they are, with scores ranging between 0 (less complex) and 100 (more complex). The x-axis (showing the relatedness density) represents how easily a country can build comparative advantage in a particular technology, depending on how closely related it is to other technologies the country is already strong in. The size of the bubbles shows how much each country has already specialised in a technology, using a measure of "revealed comparative advantage"(RCA), which reflects their competitive strenght in that field.

Source: European Commission, DG RTD.

Figure 3 EUs Competitive Position in Digital and Green Technologies

4.7.2 Energy, Decarbonisation and Sustainability

Europe also faces challenges with respect to meeting its decarbonisation and sustainability goals. Europe has ambitious climate targets and decarbonisation is an opportunity for Europe if it is implemented in such a way that it does not affect competitiveness and growth. European companies face electricity prices that are 2-3 times higher than those in the US and natural gas prices 4-5 times higher. This highlights the need to move away from gas and fossil fuels towards more renewable sources of energy. 15% of Europe's gas still comes from Russia and 85% of fossil fuels come from the US. This places European Industry at a disadvantage as the price of energy can be used to control the competitiveness of European companies.

It is predicted that fossil fuels will continue to play a central role in energy pricing at least until 2030. Around half of European companies see energy costs as a major impediment to investment.

The EU is a world leader in clean technologies, e.g. wind turbines, electrolysers and low-carbon fuels, and more than one-fifth of clean and sustainable technologies worldwide are developed in Europe. China, however, has ambitions to dominate the clean tech and electric vehicle markets supported by industrial policy and massive subsidises, rapid innovation, and control of raw materials (e.g. rare earth magnet materials for electric motors for cars and wind turbines).

A challenge for Europe is that it has binding legislation to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels requiring EU companies to invest in technologies that US and Chinese companies do not. The US has set a non-binding target of a 50-52% reduction below (higher) 2005 levels by 2030, while China only aims for its carbon emissions to peak by the end of the decade. Decarbonisation offers an opportunity for Europe to lower energy prices and take the lead in "clean tech", while also becoming more energy secure.

4.7.3 Security and Strategic Autonomy

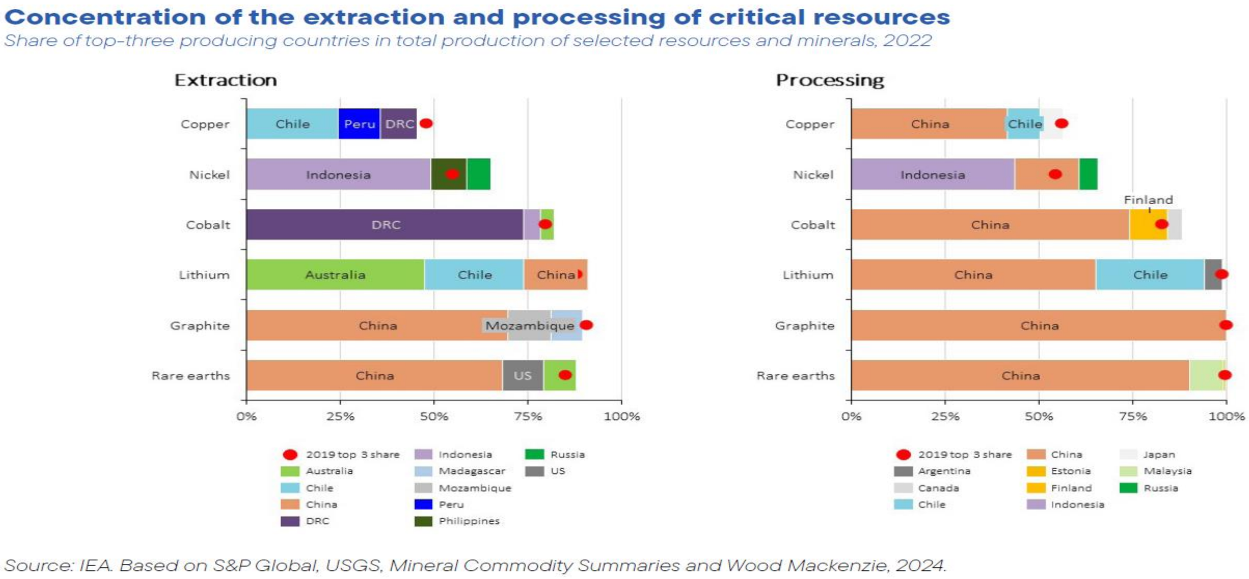


Figure 4. Extraction and Processing of Critical Raw Material

Security and strategic autonomy are important to enable growth. Already increasing geopolitical risks and uncertainties have slowed down investment and recent geopolitical shocks and trade barriers are having disruptive effects. Rising insecurity is becoming a threat to growth and freedom and Europe is particularly exposed. Europe has few sources of critical resources and relies on countries like China for critical raw materials. Europe is also highly reliant on imports of chips from Asia and the US with around 75-90% of global wafer fabrication capacity being in Asia[10]. More recently the physical security threats have been increasing, and Europe needs to prepare through military spending and in strengthening industrial capacity in defence.

There is now a global race to secure critical raw materials to maintain independent supply chains and reduce vulnerability. China already has a dominant position in processing and refining but is also investing in mines in Africa and Latin America, as well as overseas refining via its “Belt and Road” initiative[11] with USD 10 billion in the first half of 2023. The plan is to double the ownership of overseas mines containing critical minerals by Chinese companies. In response the US has deployed the Inflation Reduction Act (IRA)[12], the Bipartisan Infrastructure Act[13] as well as defence funding to reduce reliance on China. The aim is to secure the global supply chain and develop at scale domestic processing, refining and recycling capacity. Likewise, the Japan Organisation for Metals and Energy Security[14] has invested in mining and refining assets around the world and manages strategic stockpiling with powers to develop processing and refining facilities within Japan. Europe has responded with the Critical Raw Materials Act (CRMA)[15] in 2024 which aims to strengthen all stages of the European critical raw materials value chain, diversify the EU’s imports to reduce strategic dependencies, improve EU capacity to monitor and mitigate risks of

[10] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[11] https://www.chathamhouse.org/2021/09/what-chinas-belt-and-road-initiative-bri
[12] https://www.energy.gov/lpo/inflation-reduction-act-2022
[13] https://www.brookings.edu/articles/at-its-two-year-anniversary-the-bipartisan-infrastructure-law-continues-to-rebuild-all-of-america/
[14] https://www.jogmec.go.jp/english/
[15] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

disruptions to the supply of critical raw materials, and improve circularity and sustainability.

The EU relies on foreign countries for over 80% of digital products, services, infrastructure and intellectual property with a particular dependency on semiconductors. Although some EU Member States are leaders in photolithography, chemistry and machinery, there is a reliance on South Korea, Taiwan and China for chip manufacturing.

To provide resilience the EU needs to coordinate preferential trade agreements and direct investment with resource-rich nations, build up stockpiles in selected critical areas, and create industrial partnerships to secure the supply chain of key technologies. This is challenging due to the large number of Member States who each have a veto, national priorities and the slow policy making process within the EU which on average takes 19 months from Commission proposal to signing of an adopted act. Care thus needs to be taken to avoid regulation that affects competition as this stimulates productivity, investment and innovation. Already regulation is seen by more than 60% of EU companies as an obstacle to investment, with 55% of SMEs flagging regulatory obstacles and the administrative burden as their greatest challenge[16].

At the same time, Europe must accelerate the shift to a circular economy to reduce its dependence on raw materials and extend the useful lifetime of materials already in circulation. This means redesigning products and processes for durability, repairability and reuse, and investing in industrial symbiosis across sectors. A more circular approach can mitigate supply risks for critical materials, reduce exposure to volatile input prices, and cut emissions throughout value chains. It will also help Europe maintain strategic autonomy in key industries where access to raw materials, many of which are concentrated outside the EU, has become a geopolitical lever.

4.7.4 Resilience for Defence

Figure 5. European Defence Readiness

Recent rapid geopolitical shifts have led to the European Union taking responsibility for its own security, increasing defence spending and stepping up preparation activities to protect its citizens to ensure long term security. The Niinistö report "Safer Together - Strengthening Europe's Civilian and Military Preparedness and Readiness"[17] highlights a number of recommendations to prepare Europe for a more dangerous world. This has led to the "White paper for European defence - Readiness 2030" being issued[18]. This sets out a vision to rearm Europe by ensuring the European defence industry can indigenously produce the necessary military hardware it needs at the required speed and volume as well as supporting the current conflict in Ukraine. Investment in European defence is targeting lasting peace and long-term stability, however, it also boosts technological innovation, supporting European competitiveness, promoting regional development and powering economic growth. The white paper outlines 3 key areas of action to strengthen the defence industry and close gaps:

- **Closing capability gaps and supporting the European defence industry**, including simplifying regulations and streamlining industrial programmes.

[16] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[17] https://commission.europa.eu/document/download/5bb2881f-9e29-42f2-8b77-8739b19d047c_en?filename=2024_Niinisto-report_Book_VF.pdf
[18] https://ec.europa.eu/commission/presscorner/detail/en/qanda_25_790

- **Deepening the single defence market** and accelerating the transformation of defence through disruptive innovations such as AI and quantum technology.
- **Enhancing European readiness for worst-case scenarios**, by improving military mobility, stockpiling, and fostering operational cooperation across the EU.

The ReArm Europe Plan/ Readiness 2030[19] will boost defence funding by EUR 800 billion by giving EU countries more financial flexibility to increase defence spending, access to EUR 150 billion in loans for missile defence, drones and cyber security as well as European Investment Bank Support for defence and security projects.

4.7.5 Skills

Around a quarter of European companies report that they have difficulties in finding employees with the right skills and over 3 quarters report that even newly recruited employees do not have the required skills[20]. Many of these lacking skills relate to ICT. This is a barrier to investment and there is a significant shortage of ICT specialists with around 42% of Europeans lacking basic digital skills, including 37% of those in the workforce. Decarbonisation will also require new skills sets and job profiles. Positively job vacancies for clean tech manufacturing in the EU doubled between 2019 and 2023, however, 25% of EU companies reported labour shortages in the third quarter of 2023. In the 2035 timescale it is expected that there will be shortages in highly-skilled, non-manual occupations to replace retiring workers[21].

4.8 European Competitiveness Compass

To address identified issues of competitiveness the EC launched the Competitiveness Compass in January 2025[22]. The Compass pursues two broad goals to upgrade exisiting policies and to simplify procedures in Europe to speed up implementation. Policy changes are needed to accelerate key areas as shown in Figure 6.

Figure 6. EC Competitive Compass

In some areas, existing policies will need to be upgraded but in others a step-change is required to adapt to new realities. It will also be necessary to find new ways of working together to increase the speed and quality of decision-making, simplify frameworks and rules, and overcome fragmentation. The aim is to try and address some of the stuctural issues Europe has in competing with the US and China by aligning national policies on taxation, labour markets, investment and industrial policies. The Compass sets out an approach and a selection of flagship measures to boost competitiveness:

- Closing the innovation gap.
- A joint roadmap for decarbonisation and competitiveness.
- Reducing excessive dependencies and increasing security.

Manufacturing-as-a-Service (MaaS) plays a catalytic role in realising the goals of the European Competitiveness Compass. As a digital-first, flexible manufacturing model, MaaS directly supports the flagship priorities, closing the innovation gap by enabling rapid prototyping, agile scaling and wider

[19] https://commission.europa.eu/document/download/e6d5db69-e0ab-4bec-9dc0-3867b4373019_en?filename=White%20paper%20for%20European%20defence%20%E2%80%93%20Readiness%202030.pdf
[20] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[21] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[22] https://ec.europa.eu/commission/presscorner/detail/en/ip_25_339

participation of SMEs in high-tech value chains. It contributes to the joint decarbonisation–competitiveness roadmap by reducing overproduction, optimising resource use, and promoting circular manufacturing practices. Crucially, MaaS strengthens Europe's industrial resilience by reducing excessive dependencies, allowing on-demand, nearshore production and decentralised capacity that mitigates reliance on single suppliers or hostile regions. By embedding MaaS into national industrial strategies, the EU can not only simplify production logistics and lower market entry barriers, but also create the foundation for a more sovereign, digitally integrated manufacturing ecosystem. This aligns with the Compass's push for policy coherence, faster implementation, and long-term competitiveness.

5 Potential Impact of MaaS on European Manufacturing

5.1 Potential Impact of Scaling MaaS on Economics of European Manufacturing

Considering the aims of boosting European competitiveness and addressing the pressing problems that Europe faces the wider implementation of Manufacturing-as-a-Service may bring opportunities in terms of life cycle management, management of regional supply chains and collaboration between companies to share inventories and equipment. Facilitated by appropriate policies, for instance widescale adoption of digital product passports, MaaS could provide a manufacturing model that would go hand in hand with Europe's goals of the Twin Transition. Two important features of the MaaS, increased flexibility and decentralisation, provide a chance for European manufacturers to make their businesses more resilient to geopolitical changes and challenges. These features also point to some clear advantages that MaaS might have over more traditional centralised manufacturing.

Manufacturing-as-a-Service is characterised by its high flexibility from the perspective of customers. This industrial strength allows for highly adaptable and customisable manufacturing processes, enabling rapid responses to changing market demands and technological advancements, including easy change of providers if required. Additionally, MaaS provides reduced operating and logistics costs for customers by leveraging local manufacturing capabilities reducing transportation and storage expenses. Another notable strength of the approach is in promoting increasing geographic smart specialisation, which fosters regional innovation and efficiency by allowing specific areas to focus on their strengths. Furthermore, MaaS may enhance product life cycle management, contributing to better environmental outcomes by simplifying product upgrades and recycling. MaaS is also characterised by the need for low capital cost investments.

5.2 Potential Impact of Scaling MaaS to Advance Decarbonisation and Sustainability of Industrial Production

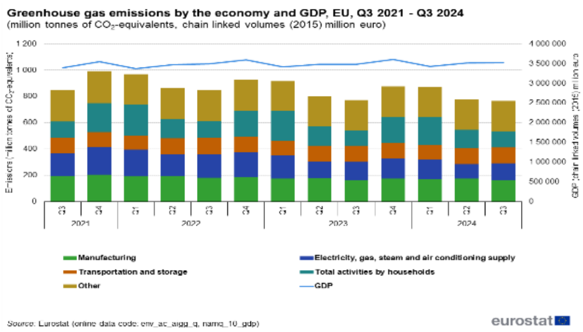


Figure 7. Greenhouse Gas Emissions in the EU Q3-2021 to Q3-2024

In the third quarter of 2024, EU economy greenhouse gas emissions were estimated at 767 million tonnes of CO_2-equivalents, a 0.6% decrease compared with the same quarter of 2023 (772 million tonnes of CO_2 equivalents), while the EU's GDP registered a 1.3% increase[23].

The environmental impact of manufacturing plays a large role, not just from the energy consumed in production, but also from carbon emissions from

[23] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU

transportation of raw materials, supplies and parts through complex supply chains. As a result, industry is striving to reduce carbon footprints and increasing numbers of organisations and consumers are prioritising sustainable, environment-friendly business practices. Notably, sustainability is a win-win for both the environment and for industry in that it reduces energy consumption and transport costs. As a consequence companies are increasingly using AI-enhanced lifecycle orchestration systems to optimise resource usage and emissions to adjust production processes dynamically based on energy market signals, material availability, and emissions impact. The adoption of MaaS, in particular, offers a powerful mechanism to accelerate industrial decarbonisation by shifting away from traditional, centralised production to on-demand, distributed, and lifecycle-aware manufacturing ecosystems. It addresses not just the energy used in production, but also the significant emissions embedded in logistics, overproduction, and waste across complex global supply chains. By bringing production closer to the point of use, MaaS reduces transport emissions and mitigates dependence on carbon-intensive shipping. MaaS models also reduce the number of Stock Keeping Units (SKUs), facilitate just-in-time manufacturing, and align with product-as-a-service approaches that extend asset life and lower carbon intensity per unit delivered. At the core of this is data transparency and Digital Product Passports enable the traceability of material origin, CO2 footprint, energy usage, recyclability, and regulatory compliance across every phase of the product lifecycle. These passports allow both consumers and B2B buyers to make informed, environmentally responsible decisions and provide a foundation for automated compliance with EU regulations. Engaging in environmentally conscious practices creates tangible business benefits with consumers becoming more willing to pay higher prices for sustainably produced products.

5.3 Potential Impact of Scaling MaaS to Advance Circularity and R-cycle Services

More than 100 billion tons of resources (metals, minerals and fossil fuels to organic materials from plants and animals) enter the economy every year and only 8.6% gets recycled and used again[24]. About 45% of global greenhouse gas emissions come from product use and manufacturing, as well as food production. Use of resources has tripled since 1970 and could double again by 2050 if business continues as usual. We would need multiple earths to sustainably support our current resource use.

The circular economy action plan (CEAP)[25] is one of the main building blocks of the Europe's Green Deal agenda for sustainable growth. The EU's transition to a circular economy will reduce pressure on natural resources and will create sustainable growth and jobs. It is also a prerequisite to achieve the EU's 2050 climate neutrality target[26] and to halt biodiversity loss. Research shows that the circular economy offers, already in 2030, a 4.5 trillion economic opportunity by reducing waste, stimulating innovation and creating employment[27]. Value retention processes ("R-cycle" services during-use, at end-of-use or end-of-life, such as repair, refurbishment or remanufacturing) are key activities of the circular economy with a high impact on sustainability. For example, remanufacturing has significant environmental benefits by averting millions of tonnes of CO_2 emissions, diverting large amounts of products away from landfill and preventing use of virgin materials. A high proportion of the worked material of a remanufactured good (typically up to 80%) is retained from the original core product. This is associated with a similar reduction in energy required and savings in emissions. With an EU

[24] https://www.circularity-gap.world/2024
[25] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
[26] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en#:~:text=The%20EU%20aims%20to%20be,to%20the%20European%20Climate%20Law%20.
[27] https://newsroom.accenture.com/news/2015/the-circular-economy-could-unlock-4-5-trillion-of-economic-growth-finds-new-book-by-accenture#:~:text=NEW%20YORK%3B%20Sept%2028%2C%202015,consumption%20while%20driving%20greater%20competitiveness.

market potential of EUR 90 billion by 2030, remanufacturing is expected to become an increasingly important aspect of the future manufacturing industry[28]. Value retention processes need largely to be locally or regionally provided. Their viable provision and upscaling require local operations/services and local providers in industrial settings[29].

Digital strategies underpin the circular economy. Digital product passports will play a key role in supporting the transition to a circular economy by promoting transparency, traceability, and sustainability in product production and consumption. Overall, the adoption of digital product passports is still in its early stages, however, they have the potential to revolutionise the way companies provide R-circles for their products in a circular economy.

MaaS approaches are not yet applied in most R-cycle services, as they involve more complex relationships between stakeholders in the Circular Economy and require open but secured data sharing between stakeholders (as provided by Data Spaces). Distributed MaaS could be a future enabler to support upscaling of circularity and partnering between OEMs and local SMEs.

5.4 Potential Impact of MaaS on Resilience

MaaS strengthens supply chain resilience by enabling decentralised, data-driven and demand-responsive production. Through decentralised production approaches manufacturers can take production to local markets or customers faster and avoid risks caused by long, rigid, global supply chains. Already this is resulting in a shift away from mass production in low-cost countries to local production of components. This has become increasingly important in recent years due to geopolitical instability and tensions, energy volatility, trade wars and armed conflicts, e.g. in Ukraine, disrupting global supply chains. As a result, the cost of purchasing components globally can increase rapidly due to increased energy costs and transport costs.

MaaS can increase resilience of European supply chains, avoid long transport distances and support local production networks. Through distributed production capabilities, federated trust frameworks and real-time coordination MaaS allows companies to quickly reconfigure their operations across regional nodes. AI-based orchestration tools can provide predictive scenario analysis, recommendations and real-time adaptability. Local production networks are more agile, adaptive, and autonomous, capable of rerouting workflows and absorbing shocks from transport disruptions, material scarcity or regulatory fragmentation. Resilience can also be reinforced by asset and capability orchestration across MaaS networks to exploit allocation of underused machines, certified processes, and available skilled labour.

One of the most visible enablers of resilient MaaS is 3D printing. It reduces dependencies by consolidating multiple parts into one process, lowering complexity and reducing the number of suppliers and transport legs. This has a significant impact on supply chains, decreasing complexities, saving on production costs, enhancing lead times and reducing time-to-market. A key benefit is that the supply chain becomes much more agile which allows rapid adaptation to change in the market and greater resilience. 3D printing is also greener and more energy-efficient reducing carbon footprint while at the same time being more sustainable in terms of resources as it creates almost zero waste. By adopting local “on demand” production approaches the risk of overproduction and creation of excess inventory is reduced. The lower number of Stock Keeping Units required for production also has a major impact on warehousing and logistics with potential to overcome tariffs set in trade wars. 3D printing also offers other benefits. Since it does not require significant tooling, it gives manufacturers much more freedom to tailor products to clients' specific requirements and enhance the customer experience. This is driving increased client engagement in the entire design and production

[28] https://www.remanufacturing.eu/assets/pdfs/remanufacturing-market-study.pdf
[29] https://circulareconomymonth.ca/resource-library/towards-a-circular-economy-value-retention-processes/

process allowing customers to build resilience into their products.

5.5 Summary of Potential MaaS Impacts

The identified potential benefits of MaaS approaches are:

- The adoption of MaaS approaches can provide significant economic benefits for European Manufacturers.
- MaaS can become a key enabler for speeding-up and scaling-up circularity and the provision of R-cycle services.
- Sustainability becomes an integral part of MaaS approaches, leading to optimal sustainable industrial production and supply for all new products.
- MaaS increases the resilience of supply by strengthening local European production networks of SMEs.

6 MaaS Roadmap for Twin Transition

The adoption of MaaS promises many potential benefits in line with the proposed twin transition being promoted by Europe. Key to this will be to put in place the right conditions to speed up scaling of MaaS, creating a critical mass of expertise, supported by suitable policy measures that accelerate the uptake of MaaS in strategic areas of importance for Europe. This will support strategic autonomy in manufacturing and also strengthen the activities towards a Circular Economy.

The MASTT2040 project has investigated and analysed aspects of future scenarios which exert the highest impact with respect to key EC goals, e.g. circularity, sustainability, resilience, human-centred manufacturing, etc. This was done via a Delphi study and via a number of workshops to provide a comprehensive picture of the opportunities and challenges for exploitation of MaaS in the future across scenarios. The pathways to realise the most impactful contribution of MaaS to the manufacturing industry's development towards the twin transition have also been analysed. Roadmapping has been performed drawing upon key stakeholders from industry (both SMEs and Midcaps), associations (EFFRA, etc.), standardisation bodies, academia and networks such as the European Digital Innovation Hubs (EDIHs).

The roadmapping workshops focussed on three timeframes (present-2030, 2030-2035, 2035-2040) with the aim of analysing high-impact aspects, their relevance for the future, different stages of developments and gaps to successful achievement. This includes drivers, markets, research needs, enabling digital technologies, standards and investments. The data standardisation needs identified are being further elaborated in MASTT2040 work going forward.

6.1 The Manufacturing-as-a-Service Business Model

2040 Vision statement of the MaaS business model

"The 2040 vision of a Manufacturing as a Service (MaaS) value network is to provide on-demand, flexible production of high quality parts within precise cost and timescales to customers via a flexible, efficient, and accessible manufacturing ecosystem that exploits digital technologies at all levels, real-time data, and decentralised production capabilities. A future MaaS in 2040 could provide a fully digitalised and highly autonomous ecosystem where artificial intelligence and machine learning algorithms will control the pre-production, production and post-production processes as well as predict market needs, optimise raw material procurement, and automatically adjust production schedules, driving cost reductions, accelerating innovation cycles, and making manufacturing more agile and customer-centric.

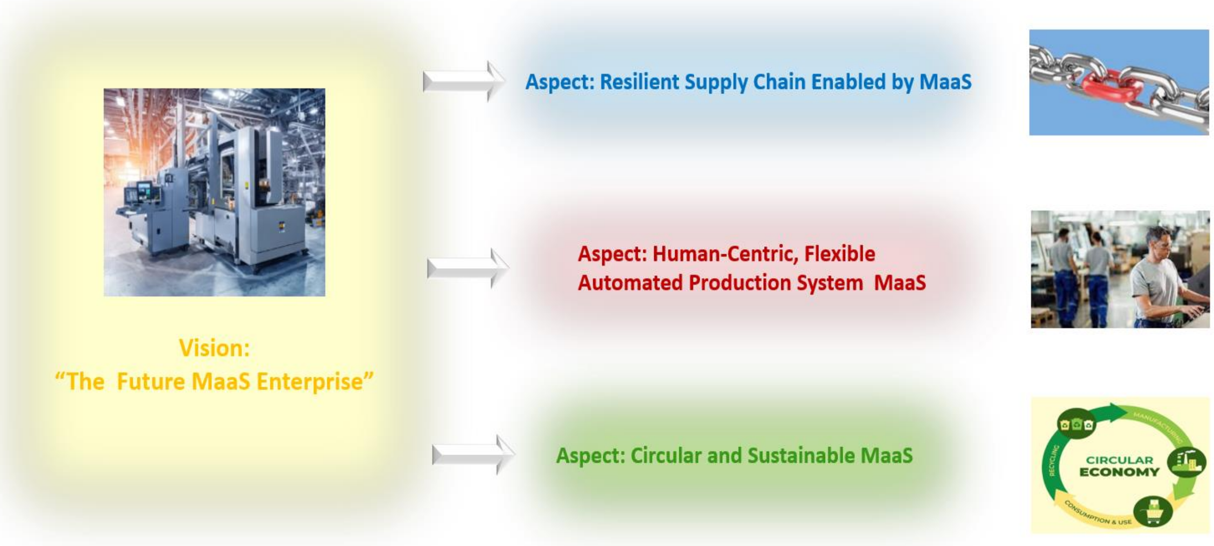


Figure 8. MaaS Vision and Aspects Considered

MaaS can provide greater resilience to geopolitical instability affecting interrelationships and access to raw materials through flexibility in manufacturing networks and adoption of sustainable and circular supply chains. MaaS can also benefit from collective learning and knowledge sharing within ecosystems and as well as creation of interdependencies. The adoption of MaaS also changes the role of humans within the production process with implications for skills development and breadth of skills required."

Characteristics of MaaS in 2040

The MaaS enterprise offers an on-demand ecosystem of manufacturing micro-services enabling flexible, on-demand production of custom parts and components with short lead time. The manufactured goods can be complex and fully customised. A key characteristic is that the MaaS enterprise can face short-notice requests for both low volume and high volume orders. This requires the enterprise to have extreme flexibility and a high degree of automation to quickly reconfigure and scale up its office processes and production system depending upon requirements and to quickly configure for bespoke product production. This requires a high degree of digitisation and interoperable platforms to allow the rapid sharing of information with customers, the ability to integrate with other suppliers if required, and to be able to rapidly enter into business agreements to fulfil new orders appropriately. Data sharing at all levels is thus core leading to concepts of collaborative productivity and sustainability. Core company values are to provide a 'what you see is what you get' (WYSWYG) capability with fast turnaround and with competitive pricing.

Other Services That May Be Offered

The range of services offered may go beyond the pure manufacturing process, extending across the value chain, for example providing product design services, with opportunities for after sales support and product maintenance if the company has appropriate capabilities. Other service opportunities are also present such as data as a service, manufacturing operations as a service and logistics as a service. Another form of service provision is the provision of equipment as a service to manufacturers from machine builders. This is so that manufacturers do not incur the high capital costs of purchasing equipment but rather pay for equipment on a usage basis, moving this financial risk to the equipment manufacturers. In practice, this service approach is challenging as finance companies are unwilling to lend money to support this as companies face the risk of underutilisation of machinery.

Dependencies

A MaaS ecosystem is strongly dependent on an efficient mechanism for providing its services such as open source systems and an efficient interface with customers to provide fast quotations based upon integration with design and manufacturing software (computer-aided design (CAD)/computer-aided manufacturing (CAM)) that the company and its clients use. Interoperability is a key factor as to maximise the client base it is necessary to support a myriad of different software packages that clients use. Fundamental to a service company's strategic plan is to be able to anticipate changes in demand from customers and to constantly innovate with respect to manufacturing technologies to improve efficiency and services provided to meet ad hoc orders. Companies may also exploit data mining from a variety of data sources, including social networks, to predict market trends in order to provide on-demand services.

Core Requirements

Digitisation is core to the success for broad-based application of MaaS by 2040 in order to cover the complete design and manufacture life cycle exploiting highly digitised and automated office processes and tools for design, costing, engineering, prototyping, production, qualification and logistics. This requires all partners in the MaaS ecosystem to have a certain level of digital maturity to engage and an appropriate management mindset. Key to success is a high level of plant automation, and the customisation of production requires short reconfiguration and tool change cycles, as well as short ramp-up and scale-up cycles. Such cycles need to include tests/experimental production, fast re-programming of machines and frequent updates of information to the workers. Providing inline and automated quality control to obtain appropriate certifications and qualifications is also a core requirement requiring installation of sensor systems to record production parameters of interest which can also be used to improve the production process, products and services. To support mass customisation the MaaS supply network needs to provide a mix of long-term and ad-hoc co-operation relying on extensive digitalisation and exploitation of technologies like AI for optimisation and orchestration in product development, production planning and engineering, production execution and manufacturing. A key challenge is to provide a competitive price based on dynamic pricing while meeting the required degree of customisation and product quality in a short development cycle. Strategic use of regulation can be used to support strategic autonomy with respect to critical raw materials and circular economy approaches.

6.1.1 Aspect: Resilient Supply Chain Enabled by MaaS

2040 Vision statement for Resilient Supply Chains Enabled by MaaS

"The vision for a resilient supply chain enabled by MaaS in 2040 is to provide a supply chain network that can predict demand and quickly adapt to disruptions, minimise risk, and recover effectively when faced with challenges. This vision depends on agility and flexibility, end-to-end visibility, predictive analytics, risk management, communication, collaboration, redundancy and sustainable practices. Optimisation is required on a number of levels to minimise reaction time, recovery time, logistics and lost capacity."

Characteristics

Resilience in the supply chain is vital and an association of companies can act as a production and/or innovation network to form a resilient MaaS enterprise. The supply chain for the MaaS may be totally based in Europe or it may cross world-wide borders. Companies flexibly co-operate as and when required, reacting to market opportunities and volatilities, developing new or improved products as well as adopting circular approaches to manufacturing. Companies can also share inventory data and trade new materials or components between businesses. To be efficient the resilient supply chain must minimise the costs and risks involved in targeting new markets with new products. The supply chain must also have sufficient redundancy in capabilities such that different partners can interchange seamlessly within the chain. Beyond pure manufacturing the supply chain may also perform research together in order to improve products and processes.

Key Driver - Flexibility at level of supply chain and its participating companies

Companies must ensure flexibility within their complex supply chain and have the ability to quickly re-configure their production lines utilising agile modular machine tools and robots to meet changing consumer requirements and be able to integrate new partners when needed. This drives requirements for flexibility at the company level and flexibility in the supply chain with the goal of collaborative productivity. The resilient supply chain enterprise may be established ad hoc to meet a short-term need and dissolved after the desired outputs have been achieved or it may be based on a long standing commercial relationship. The companies involved must join forces effectively in order to form what is in essence one business out of several separate ones in a distributed manufacturing network. This will require transparent sharing of information requiring standardisation, rules for sharing IP and other confidential information as well as a means of measuring resilience within the supply chain. As multiple partners may well have overlapping capabilities, it is important that companies are able to bid internally for selection. This automatically introduces a self-healing capability into the supply chain.

Commercial Advantages

A resilient supply chain made up of SMEs, for instance, may enable them to complement each other's strengths to produce products or be able to rival the capacities of large enterprises to bid for orders. This may also link with providing dynamic labour support between companies to meet demand and provide specific skills. When both large and small companies are combined, large companies can bring in their manufacturing capacity, while the small companies can provide flexibility and power to innovate proving modular manufacturing capacity. An example of this is through the provision of local additive manufacturing capabilities. A resilient supply chain enterprise enables a much broader product and service portfolio than any individual company could provide by working alone.

Core Requirements

Key to success is the exploitation of digitisation for communication and sharing of information to allow efficient networking, collaboration and integration. This requires a high degree of data collection and knowledge management covering the entire production cycle from design to sales and after sales service supply. Key to this is providing full virtualisation of resources through an interoperable platform that connects and synchronises critical business processes along the value chain aligning priorities, managing resource demand and supply, and exchanging critical product and production data information in order to enable fast ad-hoc decision making. This will require trustworthy data spaces that collect and exchange standardised information as well as support for contracts that allow networks to be built quickly and flexibly. This can build upon ideas already being used in existing value chain activities such as in aerospace. This heavy reliance on gathering and processing critical data, which may include commercial information, makes cyber resilience in the manufacturing network a core requirement. Means of measuring resilience also need to be introduced for key sectors of importance to Europe. This will require rules and legislation to support partnerships and equal rights to remove the barriers of sharing sensitive product data at regional, national, European and levels for different sectors.

6.1.2 Aspect: Human-Centric, Flexible Automated Production System MaaS

2040 Vision statement for Human-Centric, flexible automated production system MaaS

"The 2040 vision for human-centric flexible automated production system MaaS focuses on creating an environment that prioritises the well-being, skills, and meaningful experiences of the workers directly involved in the production process as well as end consumers. In the vision technological innovation is reinforced by worker empowerment and safety, creativity, upskilling, inclusion, job creation and seamless integration of people with manufacturing systems to promote both well-being and increased efficiency."

Characteristics

Within a human-centric and automated MaaS enterprise in 2040, there is an extremely high integration between workers and automated/supported office processes and production systems with the aim of producing products with increasingly shorter product life cycles and in a more relaxed work environment. This drives the need for seamless integration between the manufacturing systems and workers placing emphasis on human centric approaches. This starts with consumer directed approaches to manufacturing to provide increasing degrees of customisation in order to remain competitive and extensive co-operation between humans, machines and data to manage the production of the final products. This will change the role of humans creating a new type of highly adaptive knowledge worker integrated with a human friendly production environment reducing stress and automating many repetitive jobs like quotation, ordering, planning, programming and logistics. The adaptiveness of workers will be prized as much as experience and workers will have more freedom to move between MaaS entities.

Key Driver - Seamless Human Integration

The factory will be highly digitised gathering data at a much higher granularity level and exploiting optimisation of processes via data aggregation and through the use of greater automation. The exploitation of data analytics for trend monitoring, fault identification and predictive modelling will provide smart and automated ways to support production personnel in decision-making and may also improve safety. Organisational structures may need to change to reflect new worker responsibilities. Workers will also work alongside cobots allowing much greater efficiency through collaboration with machines. A key challenge is that workers will swiftly need to acquire new knowledge and the rate of human knowledge acquisition becomes a limiting factor for companies attempting to keep pace with technological progress. Approaches will be required to effectively preserve knowledge and share it between workers. Humans need to be embedded in the digital factory, provided constantly with context-relevant information from knowledge-based decision support systems or self-learning systems based on AI and Machine Learning. There is also an opportunity for companies to provide these features as services to support the production system.

Commercial Advantages

Close integration of the human within the factory allows for more efficient operation, increased productivity and better worker welfare. The need for highly skilled workers within MaaS leads to more rewarding jobs and a more motivated workforce. The operation of workers alongside cobots allows for much greater efficiency in production allowing the integration of human decision making and adaptability into the manufacturing process. This will also open up labour market opportunities for workers with physical and neuro disabilities. It is likely that workers will also have more responsibility and handle more sensitive data leading to a more empowered workforce. The democratisation of manufacturing will also open up opportunities for new start-ups to develop products leading to more entrepreneurship.

Core Requirements

A human centric approach is needed and the workers themselves need to be suitably skilled and frequently re-trained, not only in the latest production approaches, but also in sustainability and circularity. Here there are opportunities for the AI-augmented workforce and the exploitation of smart augmented reality tools placing a greater emphasis on Industry 5.0, human factors and cobots. These will need to be seamlessly linked with manufacturing execution systems (MES) and enterprise ICT systems to create a decentralised, flexible automation architecture. A key need is context-awareness of production facilities to allow better decision making based on data gathered from sensors and monitoring systems. This allows real-time adaptation of production to meet product specifications and customer demands as well as to quickly react and schedule order execution. Creativity will be valued more at work than craftmanship and workers will need to be flexible to change. Changes in education will be required to support this with the introduction of MaaS models in business schools.

6.1.3 Aspect: Circular and Sustainable MaaS

2040 Vision statement for Circular and Sustainable MaaS

"The 2040 vision for circular and sustainable MaaS focuses on creating a network of MaaS ecosystems where products, materials, and resources are continuously reused, repurposed, or recycled, with minimal waste and environmental impact. The vision closes the loop on the production process and ensures that every product and material within the MaaS ecosystem is continuously cycled back into the system, reducing the need for new resources such as critical materials, minimizing environmental impact, and creating a sustainable, regenerative economy. Within this more local reuse of materials will allow a reduction in emissions from transportation and logistics activities. This will be achieved by comprehensive exploitation of interoperability, data usage and transfer to support all aspects of the R-cycle."

Characteristics

In a circular and sustainable enterprise environmental awareness will be an essential part of corporate identity. The company's goal is to go beyond mere 'green washing' of its image and products to the introduction of environmental sustainability as a key parameter in all steps of the product life cycle, including sourcing of raw materials providing resilience to external geopolitical factors, reducing usage of materials, energy and waste in production and recycling products via a circular economy. Many companies are now concentrating on minimising resource consumption and energy efficiency is a critical performance indicator.

In particular, adapting energy demand and supply could result in major economies. Already regulation is in place for Corporate Sustainability Reporting[30] and many companies have installed renewable energy sources and reduced energy and materials consumption, however, with the aid of new regulation to drive circular approaches the future circular and sustainable enterprise vision is for a step change in sustainable approaches through the adoption of R-cycles requiring much greater networking withing the supply chain.

Key Driver - Increased Environmental Awareness

Reducing cost is a key driver in the minimisation of raw materials usage, energy, water and production of waste. Already new approaches are being pioneered in areas such as 3D printing, however, the drive towards zero waste within factory environments could in future be driven by factories striving to achieve zero waste certification. New policies for "buyback" of products for recycling or product rental and return-to-recycle will increase sustainability on sourcing and create stronger bonds with customers. This will lead to dynamic ecosystems for circular manufacturing and already coming regulations, such as Digital Product Passports, are driving this change. This will lead to digital circular trade hubs and urban mining networks to recover raw materials with priority being given to rare earth materials. Regional repair hubs will also allow the repair of products to keep them in use longer, extending their lifetime in the marketplace and reducing waste. These new green manufacturing production networks may exploit the use of materials banks, local production services and remanufacturing of parts. This will require the creation of software tools and platforms to support integrated R-cycles. At the design level modular design approaches are required to create products that are designed from the outset for greater reuse considering sustainability in the design itself and this may be supported by European CE marking of green products.

Commercial Advantages

With a much greater customer awareness of climate change the environmental footprint of ordered, customised products will need to be made available to customers. The footprint generated along the value-chain will become transparent to the customer who may themselves become part of

[30] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464

the MaaS ecosystem providing products back to be recycled. This will allow environmentally aware buying decisions to be made. The environmental footprint will be a key driver and decision parameter for both manufacturers and customers making the environmental implications of design, process, and buying decisions completely transparent. Customer demand for such transparency and company "greenness" will be a key factor in the competitiveness of the company as it will need to able to demonstrate its level of environmental sustainability.

Core Requirements

Key to success will be new manufacturing approaches, automation and the analysis of data from a large number of sources based on advanced AI to optimise the environmental footprint of manufacturing processes in real time to steer production towards minimal environmental impact. This requires extensive digitisation and exploitation of sensors, inspection and measuring technologies to gather relevant environmental impact and process data. Keeping record of the origin and history of products, components and raw materials as an additional aspect of environmental awareness can be used as a marketing advantage and to ensure that critical materials are kept in Europe. This requires a fundamental shift in societal engagement in a circular economy.

In summary manufacturing in 2040 will look much like manufacturing today. There will still be large-volume, low-mix processing which provides economies of scale. However, the competitive dynamics of manufacturing are likely to change as machines become smarter and more interconnected. This will allow increased cooperation, distributed production systems, and greater management and reuse of resources. New business models based on MaaS will compete with traditional contracting mechanisms to share value creation and this will change the roles and responsibilities across the supply chain. Finally, a key enabler in all of this will be data for decision-making, design, production and the circular economy.

6.2 2040 Future Roadmap

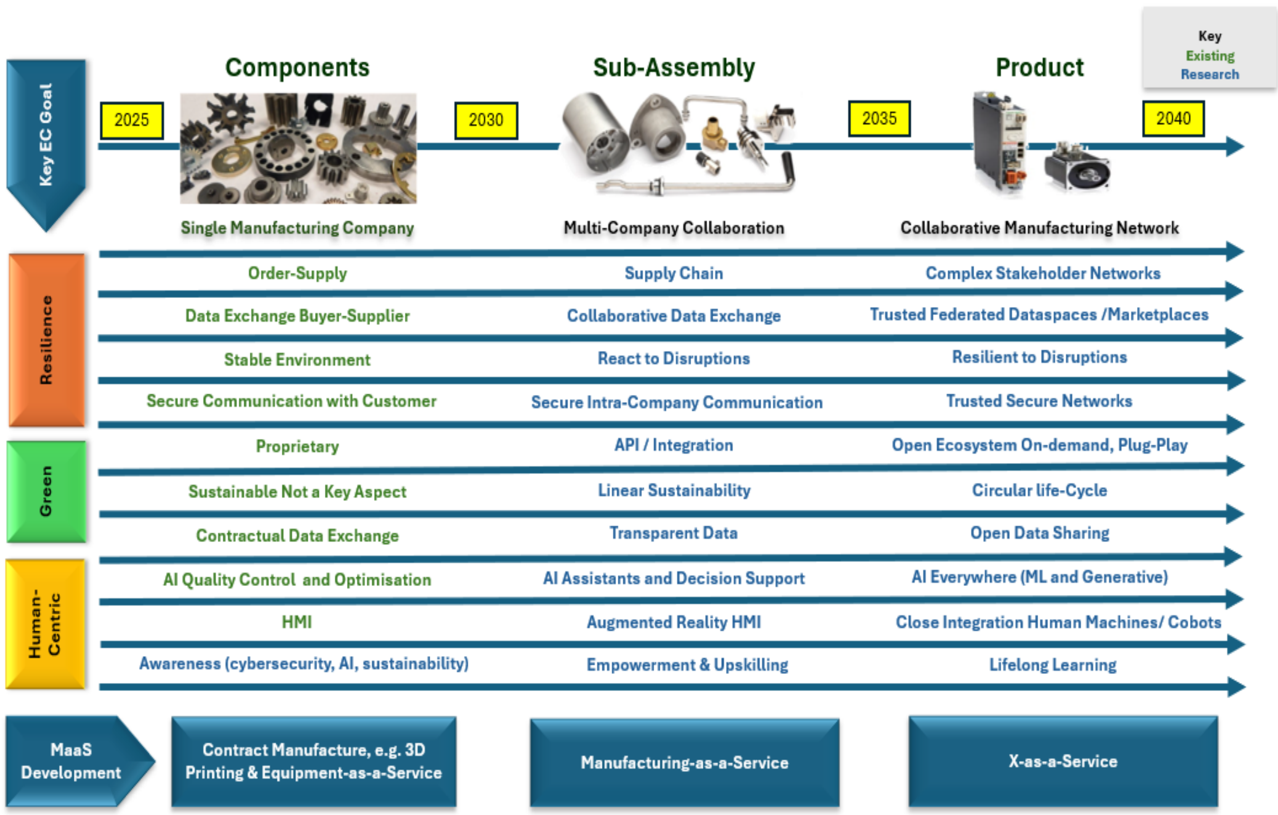


Figure 9. MaaS 2040 Roadmap

Going from today's capabilities in the marketplace it is expected that there will be much more collaboration and data sharing between companies in the future to go beyond just manufacturing of components, to manufacturing of sub-assemblies and complete products in a service-oriented culture as shown in Figure 9. This will rely on changes within manufacturing and advances in technology to enhance resilience, sustainability and circularity as well as human centric aspects.

In future:

- Manufacturing operations will exploit edge and cloud assets with more interoperability between systems and less reliance on proprietary systems. Security will become a key aspect of such systems driven by growing awareness of threats and the Cybersecurity Act.
- Mass production and bespoke production will coexist with cost competitive mature 3D printing/additive manufacturing technologies seamlessly integrated with traditional processes.
- Quality is key and increased use of sensors and vision systems will allow more quality data to be collected and analysed to allow real-time feedback control of quality based on operating parameters. Feedforward loops will also anticipate how future steps in the operating process might be tweaked to correct or improve quality. Layer-by-layer quality approaches will be developed to ensure the quality of 3D printed parts.
- Automation will continue to replace repetitive, dirty and dangerous tasks. The cost of robots and automation systems will decline to a point where even smaller manufacturers can take advantage of them.
- Advanced diagnostics and predictive maintenance will be the commonplace and unplanned downtime will be drastically reduced.
- Production will become more localised being more closely tied to the location of raw materials or the location of the customer.
- People will still be involved in manufacturing, but their roles will be different with a knowledge of subtractive and additive manufacturing approaches, AI supported digital tools, and wearables. The use of cobots and exoskeletons will increase performance and improve safety.
- Product design will consider the need for circularity utilising modular design to allow reuse at a higher level and different more environmentally friendly materials.
- AI algorithms and simulation will increasingly optimise product design to maximise performance while minimising cost, raw material use and waste in manufacturing.
- Todays' transaction driven ecosystem will change to one based more on collaboration and relationships driven by new business models based on sharing data while also protecting intellectual property.

In the following sections the consensus of industry, research community, policy and standardisation experts who have contributed to MASTT2040 workshop activities are presented highlighting priorities for the short term (2025-2030), medium term (2030-2053) and long term (2035-2040).

6.3 Digital Technologies

With respect to the most impactful digital technologies in the short term (2025-2030) it was highlighted that with increasing digitalisation a key concern is now cybersecurity. Other key needs are agile modular machine tools and the exploitation of virtual representation via digital twins. Key to circularity in the short term is the introduction of Digital Product Passports. Data was highlighted strongly with the need for Big Data analysis for quality control and shop floor transparency. Much higher degrees of automation will also need to be supported by automated programming and planning tools. Environments for machine learning, self-adaptation and reconfigurable manufacturing will also be important.

Ongoing research activities in process and machinery monitoring, sensor development and AI will continue to contribute to digitalisation. As highlighted cyber security is a concern within industry and supporting work in this area and provision of authentication services is required.

In the medium term (2030-2035) the exploitation of Generative AI for supply chain management and healing was believed to be key, along with environments and infrastructures for machine learning, self-adapting and reconfigurable manufacturing. In this timeframe mass customisation, extensive digitalisation and much greater exploitation of AI are expected delivering better context awareness of production facilities through advances in data analytics, sensors and predictive modelling. In this timeframe the circular economy comes to the fore and to support the uptake circular practices effort needs to be put into developing digital circular trade hubs and urban mining networks.

At the same time it is also important that work is performed on developing supply chain visibility, virtual representation via digital twins and virtualisation using interoperable platforms. Data gathering will be key and to enable this work on sensor technologies is required to gather more environmental and process data. To support the new role of workers within a more digitalised factory appropriate multimodal user interfaces will be required linked with automated AI orchestration tools.

In the long term (2035-2040) the vision moves towards very high degrees of automation, exploitation of AI everywhere and augmentation of workers to seamlessly integrate them within the factory leading to a concept of the Industrial Metaverse.

6.4 Resilience, Supply Chains and Strategic Autonomy

Resilience and strategic autonomy are seen as key and in order to introduce these into MaaS ecosystems in the short term (2025-2030) there needs to be a concentration on promoting redundancy in capabilities, flexibility and sustainability within manufacturing and also investment in materials banks. In parallel with this effort is required to promote supply chain visibility, plug-and-play modularity, and uptake of local renewable energy generation. In the 2030-2035 timeframe there is a clear need for work on design for MaaS circularity. There is also a need to address security solutions for collaborative networks, e.g. secure data storage and exchange in real-time between companies. At the same time there is a need to promote the concept of distributed manufacturing and introduce circular hubs for repurposing products. Looking to 2040 creation of a “resilience copilot” for industry is suggested as a means of engendering resilience.

6.5 Circularity, Decarbonisation and Sustainability

In the short term (2025-2030) to support sustainability, decarbonisation and circularity work needs to concentrate on modular design to encourage reuse at higher levels and to increase environmental awareness as an essential part of corporate identity. Work is also required to promote the establishment of materials banks, promote supply chain visibility and the uptake of local renewable energy generation.

It is noted that in parallel there will be a need for security solutions for collaborative networks, as well as initiatives to encourage the concept of product rental and return for reuse.

In the 2030-2035 timeframe it is believed that recycling hubs and companies that concentrate on recycling will become mainstream. This will be supported by the broader application of Digital Product Passports which will guide the development of a CE mark of sustainability. In this timeframe there will also be an increased environmental awareness within society which will drive the uptake of environmental sustainability as a key parameter in all steps of the product life cycle. This will need to be supported by work on tracking of raw materials, the development of dynamic ecosystems for circularity and actions to encourage transparency of environmental design. At a more fundamental level a change in mentality is required to influence process and buying decisions.

In the 2035-2040 timeframe a fundamental change is expected with companies going beyond mere greenwashing with complete R-cycles being introduced for products. This will lead to support being provided for engineering platforms that go from design to end of life.

6.6 Human Centred Industry/Human Factors

Considering the workers in future factories in the short term (2025-2030) work needs to concentrate on social and human acceptance/trust as the factory digitises and on changing the mindset on the skills required. Ways of achieving this include re-educating employees to be in charge in a new digitalised factory and via the introduction of transformation learning projects and lighthouses. There will be much greater human interaction with machines in future which requires research work on human behaviour and interaction with machines. This will require development work on human machine interfaces tailored to different personnel, multicriteria decision support using AI, and problem and context dependent display of information. In the longer term (2030-2040) augmented reality systems are expected to provide process data to workers. The interaction with humans and collection of data will also require appropriate support for authentication and encryption in secure platforms that utilise robust security standards.

6.7 Research Needs

Figure 10. Future Factory

In the short term (2025-2030) the high levels of digitalisation and interconnectivity within MaaS business models places a greater priority on research on cyber security to support privacy and cyber resilience in manufacturing networks. Research is also required into simulation, visualisation and virtualisation (digital twins) to better understand the product and process. At the same time research is required on complexity management in complex supply chains to improve resilience. To support sustainability and circularity research work is needed in modular design to allow reuse at a higher level, circular value chains and flexible automation, robotics and manufacturing approaches to reuse, repair, refurbishment, remanufacturing, repurposing, and recycling.

To support the uptake of MaaS in the short-term education on MaaS should be introduced into the Business-school curriculum with advice being provided on how to create a project and with provision of basic learning in transitioning. The adoption of MaaS also needs to consider human centric aspects, e.g. knowledge about human behaviour and interactions with machines with machines/interfaces.

In the 2030-2035 time frame research is required in intelligent decision support systems to support MaaS business models and resiliency. With the growing awareness of sustainability research will also be needed in AI decision support for sustainable product design. The greater exploitation of automation and AI support tools will change the role of humans within factories requiring research into human centric aspects such as labour effectiveness, approaches to learning, human augmentation, human-machine interfaces as well as clear rules on ownership of personal employee data.

By 2035-2040 the expectation is that there will be extensive use of AI in all aspects of production leading to a need for explainable AI. It is also expected that AI will be used in product design for sustainability and circularity as well as in areas such as new materials discovery to reduce reliance and provide alternatives to critical materials.

6.8 Importance of Data and Standards

The manufacturing of products requires a number of interacting stages with interactions with the customer and manufacturing systems as shown in Figure 11. Manufacturing of a product requires many different activities from designing a product to ordering components and raw materials, to scheduling manufacturing processes, organising and monitoring various machining and production activities through to the delivery of parts via logistics companies. This is growing ever more complex through the use of new technologies such as AI for optimising various processes and the drive towards sustainability in terms of raw material usage, energy consumption reduction and in the adoption of new circular models for recycling products.

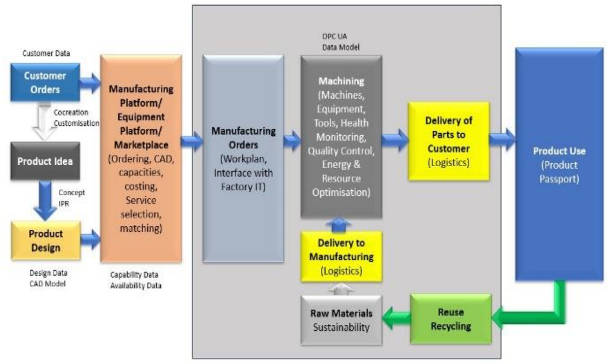


Figure 11. Key Manufacturing Activities, Data Flows and Standards Areas

To explore this the MASTT2040 project created a clickable map to provide an overview of the various activities involved in today's manufacturing chains and to highlight key relevant standards being used, as well as upcoming standards and regulation which will influence the future of manufacturing. These include:

- Standards for Customer Data Personal Data, Engagement Data, Behavioural Data, Attitudinal Data, Privacy and Security Standards, Data Governance Act, Cyber Resilience Act and AI Act
- Standards for Product Design
- Standards for Ordering, Materials Requirements Planning, Entreprise Resource Planning and Costing
- Standards for Exchange of Product Data
- Standards for Health and Safety, Connecting Machines, Machinery Health Monitoring, Quality Management, Energy Management and Environmental Standards
- Standards relevant to Logistics, Supply Chain Risk Management, Logistics Data Interoperability and Environmental Impact of logistics
- EU Sustainable Raw Materials Standards
- Circular economy standards driven by the New Circular Economy Action Plan[31], the Sustainable Products Initiative[32] and Product Passports[33].

Although many standards are in place and there are activities underway, in the short term to 2030 work needs to concentrate on interoperability between machine and ICT systems, e.g. Enterprise Resource Planning and Manufacturing Execution Systems. There is also a need to introduce approaches to data and knowledge gathering within companies to keep human knowledge and competitiveness in companies. From 2030-2035 data sharing will become far more important and standards will be required to support this. Building on this the introduction of standards for MaaS services is seen as critical as well as the development of standard reference architectures for MaaS.

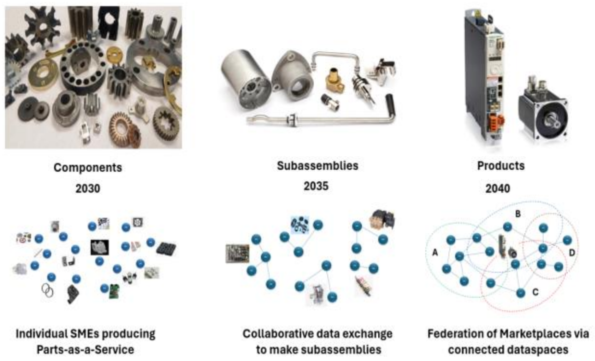


Figure 11. Expected MaaS Capability by 2040 and Growing Importance of Federated Dataspaces

Going beyond 2035, considering the increasing collaboration between companies to make subassemblies and products, absolutely core to success will be creation of trusted data spaces to allow secure data sharing to support resilience and circularity.

[31] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
[32] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en
[33] https://data.europa.eu/en/news-events/news/eus-digital-product-passport-advancing-transparency-and-sustainability

6.9 Regulation and Legislation

Key concerns for the future are the handling of data and the increasing use of AI requiring extensive data gathering across supply chains. This will require updated GDPR regulation for protection of data. AI will be everywhere and AI driven automation in particular requires consideration of AI liability. To drive sustainability and circularity legislation is required to support Zero Waste certification and to ensure that companies do not just do "greenwashing". In the 2030-2035 time frame certification of MaaS networks according to goals, e.g. safety to stop people making unsafe products, sustainability, circularity, etc., is seen as core. In the longer term as systems become more automated and the role of human workers changes legislation will likely be required to support occupational health and safety as well as work security.

There are currently many barriers to data sharing because of perceived legal and institutional barriers such as data protection, process, standards and technical barriers, as well as data quality issues, cultural barriers to data sharing, e.g. risk aversion, resource limitations which mean that companies cannot afford to implement high quality data collection and dissemination, and a general corporate reluctance to share data.

Specific regulations that have a direct impact on MaaS are:

- **GDPR and Data Governance Act** with respect to privacy of data, e.g. customer data for personalised products or data being collected through interactions between humans in MaaS production facilities or supply chains.
- The **Cyber Resilience Act** which is important due to the digital nature of products and increased data being recorded, e.g. Product Passports, and interconnectivity between actors in the supply chain.
- The **AI Act** which classifies AI into risk categories Prohibited AI, High Risk AI, Limited Risk AI and Minimal Risk AI. Potentially due to the nature of manufacturing machinery and cobots interacting with humans it is likely that applications will fall under the High Risk AI category. The Act also provides requirements for transparency and disclosure for generative AI.
- **Product Passports** will be a key driver for circularity requiring collection of data throughout a products life. The general requirements for digital product passports include having a data carrier on the product, its packaging or on documentation, with a unique product identifier according to ISO/IEC 15459:2015. This needs to be in an interoperable machine-readable, structured, and searchable format with information on the product model, batch, or item.

6.10 Skills

There is an overarching need for stakeholder education for users and decision makers with respect to MaaS, sustainability and circularity. There will also be a need to encourage a change of mindset towards creativity, innovation and open mindedness. Future workers will need support for continuous learning and upskilling on the job as well as AI augmented support systems developed with machine human collaboration in mind.

All stages of education need to be addressed and although around EUR 64 billion is currently spent on skills in the EU budget a more strategic, future oriented approach is needed that focusses on emerging skill shortages. This requires Member States to go beyond soft forms of coordination and develop skills policies based on "skills intelligence" considering existing and forecast skills gaps across regions, in order to target policies and spending appropriately. There also needs to be far more involvement of industry to develop job-specific skills.

7 Enablers and Barriers to Success

Centralised manufacturing does have some advantages as it concentrates production processes in one place allowing tighter quality control and the production of more complex products. Logistics is also simplified making supply chain management easier. It is also advantageous when considering economies of scale that optimise resource utilisation and minimise costs. A centralised approach also makes it easier to control access to sensitive information and proprietary technologies.

Although centralised manufacturing can be very efficient it lacks flexibility making it less adaptable to changes in demand or technological shifts. Having all production in one location, for instance, may be more vulnerable to disruptions from political instability, natural disasters, or other regional issues. There is also a need for high initial investment to establish large-scale facilities which is a significant economic barrier. Bureaucracy and silos within large organisations can also slow down decision-making and innovation. As the factories become optimised for large-scale production they become less effective for low-volume production and in many cases small production runs are not economic. There may also be higher transportation costs as products manufactured in a central location incur significant expenses for distribution. Centralised manufacturing can also lead to potentially higher emissions and waste production. Existing centralised factories require highly skilled labour and attracting the right people is difficult.

Adopting MaaS approaches thus offers some key advantages. The diversification of suppliers mitigates risks and ensures a more stable supply chain, providing an economic and geopolitical advantage. This needs to be supported by trusted secure data exchange within the supply chain to provide transparency and here tusted data spaces and blockchain technologies are a key enabler. There is also growing consumer demand for sustainability which drives the adoption of more sustainable and circular approaches. There are, however, a number of barriers to the adoption of MaaS. To be really successful a company has to scale quickly and this results in high capital start-up costs for MaaS providers to establish the necessary infrastructure for offering MaaS. It is also important to offer after-sales service and maintenance across decentralised locations. If operating across multiple regions a MaaS provider can be exposed to diverse regulatory environments, complicating compliance efforts. MaaS production also results in increased per unit costs as it does not benefit from economies of scale. It is also challenging to meet quality and production targets as production occurs across different locations. MaaS also struggles to supply highly complex products which are normally made in centralised manufacturing, however, as the roadmap shows advances in production are expected to make this more common in the 2040 timescale.

8 Industry Strategy and Action Plan for Future MaaS

The EU has a number of key priorities for the future of European Manufacturing focussed on four areas: sustainability, digitisation, competitiveness and strategic autonomy:

- **Fostering digitisation** - The digital transition is designed to support the green transition by enabling smarter and more efficient energy systems, optimising resource use, and supporting sustainable practices through advanced technologies like blockchain, IoT, and AI.
- **Boosting competitiveness** - The EU wants its manufacturing sector to be a global leader, competing effectively on the world stage. This includes driving innovation, improving efficiency, and reducing production costs.
- **Enhancing sustainability** - The EU is committed to a greener future, and its manufacturing strategy reflects that. The goal is to make manufacturing processes more sustainable, reducing waste and pollution, and lowering greenhouse gas emissions.
- **Strengthening strategic autonomy** - The EU wants to be less reliant on other countries for critical raw materials and technologies. This means supporting the development of domestic industries and ensuring a secure supply chain.

Key Needs

- Government support and incentives to promote innovation, digitalisation and circular approaches.
- Standardisation to enhance efficiency and interoperability within and across supply chains.
- Reliable resilient digital infrastructure to support logistical and operational needs.

- Advanced production planning and management systems to optimise manufacturing processes, reduce waste and improve efficiency.

8.1 High Impact Gaps, Priority Actions and Timescales Addressing Resilience

High Impact Actions - Critical Raw Materials

2025-2030 - In the short term it will be important to concentrate on monitoring critical raw materials via material tagging (e.g. Product Passports) to enable fast global aggregation of low quantities of critical materials. This needs to be combined with predictive tools to identify supply chain bottlenecks.

This will need to be supported with dataspaces to enable supply chain visibility, scheduling and AI tools, and creation of use cases to demonstrate how pain points can be addressed. It is noted that the Chips Act[34] has already implemented an observatory and there are lessons to be learnt from the aerospace industry.

The recommendation in the short term would be for the EC to set up an observatory, with prediction tools to flag potential scarcities in critical materials backed by an industrial dataspace covering critical raw materials within the supply chain.

2030-2035 - In the longer term it is important to concentrate on actions that identify technologies to strengthen the recovery of raw materials (supported by Digital Product Passports). Europe should develop circular value chains especially for materials where there are critical European needs.

The recommendation in the medium term is for Europe to introduce regulation encouraging the uptake of Digital Product Passports to strengthen recovery of critical raw materials and at the same time fund projects exploring end-to-end supply chain tracking.

2035-2040 - In the longer term the key actions are to develop technologies that reduce critical raw materials usage (or allow use of alternatives) while providing the same performance in products. At the same time technologies need to be improved to better mine raw materials with less wastage and to enable the better extraction and enhancement of lower grade raw materials.

The recommendations would be for the EC to fund projects that demonstrate how critical raw materials can be reduced or replaced by alternatives in products and to fund technologies to enable better mining or recovery materials.

High Impact Actions - Cyber Security

2025-2030 - In the short term it will be important to concentrate on development of AI algorithms that will allow materials flows to be monitored without providing access to confidential company data. This will require exchange of sensitive financial and investor data, trends and similarities, etc., and it is important to try and minimise the data that is exchanged. This will be enabled by security solutions to enable secure data exchange, technologies such as blockchain and potentially via the development of an EU-wide secure cloud.

The recommendation in the short term would be for the EC to explore the feasibility of an EC-wide secure cloud solution and to fund activities that support the uptake of security solutions in SMEs such as blockchain.

2030-2035 - In the longer term it is important to concentrate on actions that minimise the attack surface such as moving target defence[35] to avoid

[34] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en
[35] https://www.morphisec.com/automated-moving-target-defense/

data being intercepted and secure federated data infrastructures to support federated AI algorithms. Secure data passports that contain the minimum data necessary also need to be explored.

The recommendation in the medium term is for Europe to continue to fund research on cybersecurity to protect data. However, in addition there is a need for projects to be funded that identify how the amount of confidential data that needs to be transferred can be minimised. Smaller scale projects on federated architectures and learning have been funded by the EC, however, it is necessary to fund larger industrial scale projects to demonstrate their worth to industry.

2035-2040 - Cybersecurity is a continuum as new threats appear all the time, thus there will be a need to continually monitor and counter new threats which will require investment.

High Impact Actions - Capability Redundancy in the Supply Chain

2025-2030 - In the short term it will be important to concentrate on development of a real-time dashboard to provide information on the real-time capabilities of each supplier in the supply chain. This needs to be coupled with digital twins of the supply chain to simulate recovery strategies and the impact of disruptions. At a base level there is a need for support for companies in the supplier network to digitise so that they can exchange data and bid for work. Additionally, AI-based tools need to be developed that can identify weaknesses and stressors in the supply chain to ensure resilience. It was noted that a marketplace approach to MaaS naturally allows suppliers to be swapped within the supply chain and as products get more complex there will be a need to connect multiple marketplaces together.

The recommendation in the short term would be for the EC to fund projects that create a dashboard supported by optimisation algorithms (load balancing, etc.) to provide real-time optimisation of supply chains for resilience.

2030-2035 - In the medium term it is important to concentrate on actions that address optimisation tools that allow the best combination of suppliers in real time for specific product/component production. This needs to be supported with automatic load balancing in service selection.

This would be an enhancement of the tools produced in the recommended actions for 2025-2030 timeframe but with deployment/uptake in real cases.

2035-2040 - The expectation for the longer term is that manufacturing services will become a "black box" that can provide services and products for a wide range of customers with great flexibility and agility.

High Impact Actions – Flexibility within Individual Companies

2025-2030 - In the short term it will be important to concentrate on development of modular production systems that enable "plug-and-play" manufacturing. This will require a unified digital infrastructure going from design to delivery and the use of a digital twin management layer.

The recommendation in the short term would be to encourage appropriate standardisation for interoperability to allow exchange of information at machine level.

2030-2035 - In the medium term it is important to concentrate on the creation of a collaborative environment for manufacturing allowing multiple suppliers to come together. This will need support to educate and upskill the workforce with a broader set of digital skills.

The main recommendation in the medium term would be to encourage appropriate standardisation to allow exchange of information between companies to allow collaboration. At the same time actions for upskilling workers will be required.

2035-2040 - The expectation for the longer term is that manufacturing services will become a "black box" that can provide services and products for a wide range of customers with great flexibility and agility. It is envisaged that this could lead to "fabless models" of manufacturing like those seen in the semiconductor industry

8.2 High Impact Gaps, Priority Actions and Timescales Addressing Circularity and Sustainability

High Impact Actions - Enabling Sustainable Manufacturing and Circularity

2025-2030 - In the short term it will be important to demonstrate how MaaS can support more complex stakeholder relationships. It is also important to create use cases and publish results from these to share knowledge and provide inspiration to other companies. To support SMEs, in particular, there is a need for easy-to-use bottom-up solutions which should be provided by start-ups and scale-ups to avoid vendor lock-in to big players. The aim would be to provide open tools that can be easily integrated which focus on sustainability with features such as trade-off analysis between sustainability and cost. These tools should also have APIs (via a standardised data interface) that link to materials banks. Supporting uptake of circular and sustainable practices there is a need for stakeholder education especially for decision makers and management. There is also a need for continuous learning. Incentives, such as tax breaks, are required to stimulate companies to research into and adopt resource efficient manufacturing processes.

The recommendation in the short term would be for the EC to fund pilot projects to develop tools that promote sustainability and circular practices and to back this up by developing eco design standards. At a national level tax breaks should be provided to incentivise companies to adopt circular and sustainable manufacturing processes.

2030-2035 - In the medium term it is important to concentrate on the establishment of regional digital circular trade hubs. R&D also needs to be performed into creating circular materials that can be reused. Underpinning this there is a need to develop standards for interoperability within MaaS ecosystems.

The recommendation in the medium term is to provide regional support for industrial stakeholders to demonstrate the benefits of circular approaches, e.g. via creation of digital circular trade hubs, which can then be scaled towards the wider community.

2035-2040 - In the longer term the expectation is that knowledge driven AI will be used to support SMEs in adopting circular practices.

High Impact Actions - Increasing Environmental Consciousness in the Economy and Society

2025-2030 - In the short term it is important to develop comparison tools to support decision making that can analyse alternative sustainable/circular solutions. This will require analysis tools that calculate the real sustainability impact of different actions. These tools can then be used to organise manufacturing systems to be more sustainable. It is also important to encourage companies to make sustainability and circularity part of their strategy so that it is standard in development processes. This is linked with making sustainability and circularity part of corporate identity.

The recommendation in the short term would be for the EC to fund decision making tools for companies to optimise their processes. Initiatives are also required to raise awareness and encourage the uptake of sustainable and circular practices.

2030-2035 - In the medium term it is important to concentrate on actions that promote sustainable implementation of manufacturing supply chains. This can be through introduction of Digital Product Passports and by establishing clear guidelines for circular manufacturing processes in MaaS business models. For this to be successful there is a need to provide access to remanufacturing data and to share best practices for remanufacturing so that trusted providers can be developed that can serve several companies.

The recommendation in the medium term would be for the EC to concentrate on rolling out Digital Product Passports and investigate the development of European standards, eco labels and certification. At a regulatory level mandatory ESG (environmental, social and governance) reporting standards are needed. There is also a need for environmental impact training and this could be supported by the EC creating a European platform for exchange of best practices in sustainable production and consumption, underpinned by national and regional initiatives.

2035-2040 - In the longer term the key actions would be to provide tools that automate sustainability reporting and to also provide tools that help companies partially automate process adjustment to continuously optimise sustainability.

High Impact Actions - Transparency

2025-2030 - In the short term there is a need to put in place a methodology that allows a neutral approach to judgement of sustainability for a company or process. This is to combat companies greenwashing. The implementation of this would require a common and easy to use reporting system. Reporting should be made mandatory, but companies should be allowed to use average figures for a period of 3 years to allow them to collect real data.

The recommendation in the short term would be for the EC introduce regulation to make reporting of a key subset of sustainability data mandatory with a phased 3-year introduction.

2030-2035 - In the medium term actions should concentrate on industry assessments and legislation in order to provide guidelines and standards for reporting data for product groups (this should firstly be for a limited set of products which is then expanded over time). For reporting it is important to put in place a mechanism that allows trusted communication among participants within the circular economy. The key aim will be to report and share CO_2 footprint data transparently in a trusted way with government, customers and suppliers via a single portal so that it is only done once. This lifecycle information will enable consumers and businesses to make informed sustainability decisions.

The recommendation in the medium to long term is for the EC to implement mandatory CO_2 footprint reporting at every stage of the product and service for key products. Supporting the introduction of this the EC should fund pilots in smaller networks to better understand and demonstrate trust dynamics for exchange of data. Certification should also be explored for MaaS value chains considering emissions, social, and economic factors. There is also a need for certification to prevent unsafe products being produced.

High Impact Actions - Digital Product Passports

2025-2030 - It will be important in the short term to concentrate on supporting SMEs, providers and customers in data gathering, data analysis and knowledge management for Digital Product Passports (DPP). An enabler for this is the creation of a trusted data space for data sharing utilising open data formats that ensures data safety and security. It is also important to gather lessons learnt from early adopters which in turn will enable creation of a community of tool providers. CO_2 and sustainability data should be directly incorporated into the Digital Product Passport for transparency. The data format should be reviewed by industry associations and standardised. The data stored should also be reviewed to see how customers use the DPP to adjust processes. The aim is to identify real business benefits of using DPPs for SMEs, learning networks, and practitioners. The ultimate goal is to make “not having a DPP” an issue for a company.

The recommendation in the short term would be for the EC to concentrate on funding projects that demonstrate data gathering and trusted data exchange (e.g. trusted data spaces) of Digital Product Passport data. This needs to be backed by industry driven standardisation initiatives. The EC projects should also clearly demonstrate the business benefits of DPPs which should be widely publicised to stakeholders.

2030-2035 - In the longer term it is important to concentrate on development of Digital Product Passports for MaaS to track vehicles, components and other products. This will allow consumers and businesses to access essential information about sustainability, recyclability, and carbon footprint of MaaS solutions.

The recommendation in the medium term is for Europe to introduce regulation encouraging the uptake of Digital Product Passports to strengthen circular approaches and at the same time fund projects that create use cases for training.

2035-2040 - In the longer term the aim will be to encourage the wider scale adoption of DPPs to guide circular economy development in other sectors where MaaS is deployed.

The recommendation would be for the EC to fund projects in key sectors and demonstrate how the approaches can be adopted to make it easier for SMEs to embrace DPPs and circular practices.

8.3 High Impact Gaps, Priority Actions and Timescales Addressing Skills and Human Centric Aspects

Future Skills Embracing Mindset

2025-2030 - In the short term it is important to concentrate on human machine interaction, simulation and visualisation to address complexity management and provide greater flexibility. Skills in these areas will be essential for all university graduates. There is also a need to develop digital knowledge sharing platforms to allow MaaS stakeholders to share experience. At a technical level there is a need to standardise components to create MaaS value chains, standardise intra and inter machine communication standards and support multilingual interfaces. For trusted communications cybersecurity will be essential.

The recommendation in the short term would be to develop a "must have" set of competences for MaaS approaches within academia and industry which can be shared via a network such as the European good practice network.

2030-2035 - In the medium term personalised learning is required supported by competence tests. AI will be a common tool in this timeframe and there will be a need for trustworthy explainable AI supported by regulation for the use of AI on the shop floor. This may also require changes to occupational health and safety rules and actions to engender work security. The interaction between digital twins and humans will also become more common. There will be a need for human centric knowledge sharing in manufacturing communities of practice.

The recommendation in the medium term is for SMEs and universities to create personalised learning materials. This should be backed by a competence validation culture and certification framework.

2035-2040 - In the longer term there is a need to ensure a high level of trust for AI and machine leaning tools used for decision support. There is a fundamental need to avoid "tech overload" and it is likely that digital twins will be extensively used in conjunction with operator feedback. Workers should be empowered to give feedback on the technology via user friendly interfaces bringing about human centricity by design.

It is also essential to attract younger workers via adoption of new technologies and tools while helping older workers accept these technologies. Older workers have a lot of valuable knowledge and it is important to capitalise on this via knowledge sharing of experience between older and younger workers. There will be differences in relevance and interest between younger and older workers and management will need to be trained to understand this. Academia and national authorities should encourage an innovation economy supported by internal and external learning platforms. In the long term this will lead to the industrial metaverse.

A top-down and bottom-up approach is recommended to lifelong education with good practice and success story input from SMEs sharing insights in local languages which could be supported via Digital Innovation Hubs. Learning platforms should be funded that allow knowledge sharing between older and younger workers.

Empowering Entrepreneurs, Workers and Citizens

2025-2030 - In the short term there is a critical need for trusted data spaces to allow data sharing. To encourage the uptake of MaaS there is also a need to support joint prototyping sessions in collaborative labs and living labs.

The recommendation in the short term is to fund projects to create trusted data spaces for MaaS and activities that will promote the uptake of MaaS such as collaborative labs and living labs.

2030-2035 - In the medium term there is a need for standardisation for manufacturing services with a strong need to standardise cocreation chains.

The recommendation in the medium term is to look at existing and developing standards and see how they can be integrated to help SMEs create services and cocreation chains.

2035-2040 - In the long term automation and digitalisation will lead to completely different role for humans. There is a need to create a reference architecture for MaaS covering layers, processes, standards and toolboxes. A simpler model is required that focusses on processes and standards for Industry 5.0[36]. Creation of such a model would stimulate discussion among stakeholders from research and industry bringing together activities such as Catena-X[37] and Industry 5.0.

The EC should encourage industry along with standards bodies such as CEN-CENELEC to develop a reference architecture for MaaS.

Social and Human Acceptance/Trust

2025-2030 - To encourage social acceptance in the short term work should concentrate on the creation of trusted dataspaces for data sharing and actions to enable trust in the output from AI models. There is also a need to increase awareness of cybersecurity to demonstrate to people that their data is safe.

In the short term the key recommendation is to support training and development programmes to raise awareness of cybersecurity and AI as well as to support the creation of trusted dataspaces for MaaS.

2030-2035 - In the medium to long term there will be increased automation including automation of machine programming and production planning. A key need will be education of workers to explain how the technology supports them in their jobs rather than leading to unemployment.

The recommendation In the medium to long term is to promote the benefits of increasing automation of processes and how it enhances existing jobs to workers.

Accessible HMI Technologies

2025-2030 - In the short term there is a need to implement large-scale HMI projects in industry to demonstrate their benefits and to encourage uptake.

In the short term the EC should fund deployments of HMIs in industry leading to the deployment at a larger scale.

2030-2035 - In the medium to long term in order to support increasing optimisation of processes via tools such as AI there will be a need to gather more customer and demand data. This will need to be maintained and shared via cybersecure dataspaces.

In the medium to long term certification for MaaS value chains should be developed along with standardisation of AI for MaaS value chains. To secure data cybersecurity standards should be adopted and updated regularly to meet new threats.

[36] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en
[37] https://catena-x.net/

9 Estimated Costs of Actions

Projects	
Pilot Project	€500K-€4M
Mid-Sized (Regional) Deployment	€10M-€100M
Large Company Deployment	€200M-€500M
National Sector Deployment	€500M+
Cost of defining data standard	€150K annually

Human Centric	
Skilling/Upskilling per worker	€2K-€20K
Human-machine collaboration training (e.g., cobots, digital tools)	€2K–€10K per worker
Reskilling for AI, automation, and digital tools	€5K–€20K per worker
Soft skills, problem-solving, and leadership (lean, agile teams)	€1K–€5K per worker
Augmented reality (AR)	€1M–€5M per line/factory
Human-in-the-loop AI or decision support systems	€2M–€20M per company
Worker dashboards for real-time data feedback	€500K–€5M

Circularity	
Product design for reuse/recyclability	€500K–€10M per product line
Recycling and re-manufacturing facilities	€10M–€500M per plant
Materials Science Research	€10M+
Advanced Sorting/Digital Twin	€1M–€5M per company
Certification for Circular	€500K+

Resilience	
Diversifying Suppliers	€1M-€10M
Nearshoring	€10-€100M+
Supply chain visibility based on Digital twins, IoT sensors, predictive analytics, blockchain for traceability, etc.	€5M–€100M
Flexible Manufacturing Systems (Smart manufacturing equipment, modular design)	€10M–€100M per facility
Cybersecurity & Risk Management depending on size of company and data sensitivity	€0.5M–€10M annually

Table 1. Investment Guide

The gaps identified will require strategic investment from industry, banks, Venture Capitalists, national governments, the EC and the European Investment Bank. In order to assess the scale of these investments needed a guide table has been created (see Table 1) to identify typical costs of funding projects, skills training, and standardisation as well as larger scale actions to support circular practices and resilience. These investments need to be assessed based upon their potential returns which go beyond pure economic factors to include impacts on strategic autonomy, defence and climate change.

10 Concluding Remarks

It is clear that the adoption of MaaS business models will have a positive impact on the European manufacturing industry with respect to digitisation, circularity, sustainability and decarbonisation. Such models require new skills in manufacturing, combining software development, data analytics and Artificial Intelligence with manufacturing expertise. Existing MaaS companies are concentrated on growing their business as a priority (scale-up is key) and are only weakly driven by green goals. Although sustainability and carbon emissions reporting have become important to the manufacturing industry as a whole, with examples of approaches to decarbonisation, energy reduction, resource optimisation, and waste reduction, there are few examples of circularity. Here the 3D printing industry (key exponents of MaaS) are leaders in the reuse of materials grinding up products to reuse the materials in new products. The wider adoption of MaaS presents opportunities for life cycle management, management of regional supply chains, and collaboration between companies to share inventories and equipment. Here it is believed that the introduction of product passports could be a key enabler. Digital product passports and digitised services are expected to play a critical role in supporting R-cycles (inner circles of the circular economy) aimed at reducing waste and supporting value retention strategies for the resources by focusing on reusing, repairing, refurbishing, reconditioning and remanufacturing products.

Strategic Autonomy

The world has become more fragmented and multipolar. There has been a shift from the "rule of order" to the "rule of power" and this is reflected in trade tariffs being imposed. It is predicted that there will be a shortage of energy by 2030[38] and currently Europe is reliant on Russia and the US for gas and oil. This needs to change with the large-scale adoption of renewable energy. Already this is being driven by policy actions such as the Clean Energy Deal[39] and the Affordable Energy Action

[38] European power demand to rise by 25-50% by 2035 | en:former
[39] https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en

Plan[40]. For strategic autonomy within supply chains there is a need to reduce reliance on critical raw materials and also develop interdependencies with key suppliers. The adoption of the circular economy is essential in order to address shortages and remove reliance on supply of critical raw materials from other parts of the world. It should be noted that it may be unrealistic to have a totally European value chain, but a target of 80% European should be an aim with a key requirement being affordability and security of supply. Finally, boosting R&I for alternative materials or processes will be crucial to substitute critical raw materials.

Data and Standardisation

Data sharing with customers and within supply chains is core to MaaS. Standards are required to drive interoperabilty within factories to flexibly connect machines. Standardisation is also required to allow collaboration between partners in supply chains addressing areas such as semantic interoperability for exchange of data. There is also a need to protect Intellectual Property and trusted industrial dataspaces are seen as a key enabler for the future. Building on this the introduction of standards for MaaS services is seen as critical as well as the development of standard reference architectures for MaaS.

Financing

There are limited funds and thus any strategy needs to focus on core areas that need addressing and tangible actions are required that are affordable and scalable. A long-term investment plan is required and this is challenging when there is a lot of political uncertainty, however, the uptake of MaaS provides benefits with respect to strategic autonomy and resilience which are in tune with new initiatives targeted at defence. To ensure that Europe makes the most of the opportunities that lie ahead cost-effective approaches are required to introduce new technologies and business models.

Regulations

Regulations need to be introduced pragmatically to ensure that they do not affect competitiveness but are used to “nudge” industry towards goals such as the circular economy, e.g. Product Passports, and on waste collection to achieve strategic goals but without stifling innovation and slowing down change. Cybersecurity is important for resilience and the Cyber Resilience Act will have important impacts on European Industry. The need for data sharing and trusted data spaces highlights the importance of the Data Governance Act. It is predicted that AI will be used ubiquitously across manufacturing by 2040 so the AI Act will also have strong implications for Industry. It is important that regulations are introduced with care and with close Industry consultation as an unstable legal framework also leads to lack of investment.

Skills

Digitalisation and the uptake of new approaches is driven by people with the right skills. Currently there is a shortage of skilled people and by 2040 the workforce is likely to reduce significantly requiring productivity gains to be achieved via the close integration of human workers with factory systems. This will require new skills in digital technologies and a more multi-dimensional approach to knowledge covering basic skills, product knowledge skills including green manufacturing and analytical skills to understand and interpret data being presented by factory systems. Data has been highlighted as being key in the future, but skilled people will be required to unlock the insights from this. Notably in education it takes typically 10 years to see change, so activities need to start now in order to support the MaaS factory vision for 2040.

Policy Actions

Overall, the challenges faced present a coordination problem. AI is seen as a key enabler for the future and Europe is behind with respect to the US and China. Already a raft of policy actions have been introduced, e.g. AI and Cloud

[40] https://energy.ec.europa.eu/publications/action-plan-affordable-energy-unlocking-true-value-our-energy-union-secure-affordable-efficient-and_en

Development Act, the AI Act and Strategic Roadmap on AI, however, the technology is moving very fast and is expected to accelerate so European Industry needs to act quickly to exploit the benefits of the technology and improve productivity. The Competitiveness Compass is seen as a positive move and needs to be supported by more actions such as a Competitiveness Fund[41] to accelerate the uptake of digitalisation, circular approaches and MaaS business models. Supporting this Europe needs to carefully adopt trade policies that keep barriers low, create a level playing field, ensure access to critical resources and protect key supply chains. Policies will need to be pragmatic with trade openness towards countries that can provide key digital goods, processors, AI tools, services and infrastructures and more defensive where necessary to offset state-sponsored competition abroad, in line with the new EU Economic Security Strategy[42] and by providing support for the Strategic Technologies for Europe Platform (STEP)[43].

Outlook

With suitable support by 2040 Manufacturing as a Service (MaaS) could mature into a trusted, resilient, and adaptive industrial backbone, enabling on-demand, high-quality, and precisely timed production making it accessible to all players from SMEs to global integrators. Flexible, efficient, and open fully digital autonomous manufacturing networks governed by federated models will provide robustness to disruption. Explainable AI and machine learning will be exploited from design to post-production, forecasting demand, orchestrating supply, optimising resource use and adapting to change in real time. These ecosystems will evolve through continuous feedback loops, collective learning and shared intelligence. Trust, traceability and control will be essential through exploitation of sovereign data spaces, decentralised governance models and access rights controlled via permissions and roles. Actors will retain full control over their IP, data and services encouraging innovation. Orchestration engines will be required to match demand and supply across domains, enabling agile assembly of supply chains from distributed resources offering traditional and deep-tech, high-precision processes.

A key enabler will be standardisation so that machines, processes or capabilities are easily discoverable, semantically described and dynamically composable. Sustainability and resilience can be built into MaaS platforms considering energy, resources and raw materials usage to optimise for low-carbon manufacturing, avoid use of critical raw materials and encourage circular approaches. This will lead to change redefining what it means to work in manufacturing. Roles, skills and careers will shift as humans take on orchestration, supervision and innovation tasks supported by intelligent, secure, and transparent systems designed to empower. Human insight will, however, remain essential in hybrid decision systems combine human context with machine intelligence to enhance creativity, situational judgement and oversight.

In order to promote the successful uptake of MaaS the MASTT2040 project has identified and presented in this report the key research, policy, standardisation and skills recommendations that will lead to more resilient, sustainable and human centric manufacturing in future.

[41] https://www.effra.eu/news/fp10-to-align-closely-with-european-competitiveness-fund/
[42] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3358
[43] https://strategic-technologies.europa.eu/index_en

Summary of Recommendations

Promoting Resilience	
Trusted Data Spaces	In the short term projects should be funded by the EC to create trusted data spaces for MaaS. These should be supported by collaborative labs and living labs to promote the uptake of MaaS. At the same time the EC should encourage industry along with standards body such as CEN-CENELEC to develop a reference architecture for MaaS. In the medium term existing and developing standards should be integrated to help SMEs create services and cocreation chains. Certification for MaaS value chains that rely on AI should be developed.
Critical Raw Materials	In the short term the EC should set up an observatory, supported by prediction tools to flag potential scarcities in critical materials backed by an industrial dataspace covering critical raw materials within the supply chain. In the medium term Europe should introduce regulation encouraging the uptake of Digital Product Passports to strengthen recovery of critical raw materials backed by projects exploring end-to-end supply chain tracking. In the long term the EC should fund projects that demonstrate how critical raw materials can be reduced or be replaced by alternatives as well as technologies to enable better mining or recovery of materials.
Flexibility and Capability Redundancy	To enhance flexibility within companies in the short term appropriate standardisation for interoperability to allow exchange of information at machine level should be encouraged. The EC should also fund projects that create a dashboard supported by optimisation algorithms (load balancing, etc.) to provide real-time optimisation of supply chains for resilience. In the medium term collaboration between companies in the supply chain is key and so standardisation should be encouraged to allow easier exchange of information.
Cyber Security	In the short term the EC should explore the feasibility of an EC wide secure cloud solution and fund activities that support the uptake of security solutions in SMEs such as blockchain. Europe needs to continually fund research on cybersecurity and update cybersecurity standards to protect data from new emerging threats, however, in addition there is a need in the medium term for funded projects to identify how the amount of confidential data that needs to be transferred can be minimised. Already the EC is funding smaller scale projects on federated architectures and AI learning, however, it is necessary to fund larger industrial scale projects to demonstrate their worth to industry.
Promoting Sustainable Manufacturing and Circularity	
Sustainable and Circular Manufacturing	In the short term the EC should fund pilot projects to develop tools that promote sustainability and circular practices, e.g. decision-making tools for companies to optimise their processes. This should be backed by eco design standards. At a national level tax breaks should be provided to incentivise companies to adopt circular manufacturing processes. In the medium term regional support for industrial stakeholders is needed to demonstrate the benefits of circular approaches, e.g. via creation of digital circular trade hubs, which can then be scaled towards the wider community. National and regional initiatives are required to raise awareness of sustainable and circular practices and to provide environmental impact training. This could be supported by a European platform for exchange of best practices.
Reporting and Certification	The EC should introduce regulation with a phased 3-year introduction to make reporting of a key subset of sustainability data mandatory. In the medium to long term the EC should implement mandatory CO_2 footprint reporting at every stage of the product and service for key products. Supporting the introduction of this the EC should fund pilots in smaller networks to better understand and demonstrate trust dynamics for exchange of data. At a regulatory level mandatory ESG (environmental, social and governance) reporting standards are needed. Certification to prevent unsafe products being produced by MaaS value chains is also essential.
Digital Product Passports	In the short term the EC should concentrate on funding projects that demonstrate data gathering and trusted data exchange (e.g. trusted data spaces) of Digital Product Passport (DPP) data. This needs to be backed by industry driven standardisation initiatives. These projects should clearly demonstrate the business benefits of DPPs which should be widely publicised to stakeholders. In the medium term the EC should concentrate on rolling out Digital Product Passports and investigate the development of European standards, eco labels and certification. In the medium term Europe needs to introduce regulation encouraging the uptake of Digital Product Passports to strengthen circular approaches and at the same time fund projects that create use cases for training. In the long term the EC should fund projects in key sectors and demonstrate how the approaches can be adopted to make it easier for SMEs to embrace DPPs and circular practices.
Promoting Human Centric Aspects and Skills Development	
HMIs	In the short term the EC should fund deployments of HMIs in industry leading to the deployment at a larger scale. In the medium term research into AI decision support tools and augmented reality tools should be funded leading to collaborative working with cobots.
Skills	**A** short term goal is to develop a “must have” set of competences for MaaS approaches which can be shared via a network such as the European good practice network. At the same time actions for upskilling workers are required. In the medium term SMEs and universities should create personalised learning materials backed by a competence validation culture and certification framework. A top-down and bottom-up approach is required to lifelong education with good practice and success stories from SMEs being shared in local languages via the Digital Innovation Hubs. Learning platforms should be funded at the national and European level to allow knowledge sharing between older and younger workers. At a general level the benefits of increasing automation of processes and how it enhances existing jobs needs to be promoted to workers.