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Agile manufacturing

Joan Jané

Holly Anne Hill

IESE Business School
University of Navarra

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IESE Business School
University of Navarra

Authors

Joan Jané

Professor of the Practice of Management of Operations, Information and Technology

Holly Anne Hill

Research Assistant

Design: IESE Business School: www.iese.edu

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Abbreviations

AM: Additive manufacturing

BPM: Business process management

CNC: Computer numerical control

FDM: Fused deposition modeling

ICP: Industry cloud performance

OEM: Original equipment manufacturers

TaaS: Technology as a service

Executive summary: agile manufacturing in Europe

Agile manufacturing is becoming increasingly important in Europe as the continent faces evolving market dynamics characterized by shifting consumer preferences, shorter product life cycles, and the need for greater customization. The move away from traditional mass production toward more adaptive, flexible systems is essential for maintaining competitiveness in this fragmented and fast-changing environment. Agile manufacturing allows companies to produce low-volume, high-quality products that cater to specific customer needs, thereby addressing the growing demand for individualized products across various sectors.

The adoption of agile manufacturing is deeply intertwined with the rise of Industry 4.0 technologies, such as cyber-physical systems, the internet of things, big data, and artificial intelligence. These innovations are driving significant transformations in European manufacturing, enabling firms to optimize their supply chains, improve production efficiency, and meet sustainability goals. By leveraging these technologies, European manufacturers can adapt quickly to external uncertainties while enhancing their resilience and competitiveness.

The key drivers of agile manufacturing in Europe include technological growth, sustainability imperatives, supply chain risk management, and deglobalization. EU initiatives, such as the Digital Decade Policy and Horizon 2020, are actively promoting the adoption of advanced manufacturing technologies through subsidies and financial support. These policies emphasize the need for European manufacturers to incorporate more sustainable practices while staying at the forefront of digital and technological innovation.

This paper also explores the addressable market for agile manufacturing, segmented by region, sector, manufacturing process, and customer type. Based on both a literature review and focus groups with industry professionals, this analysis highlights regions in Europe where agile manufacturing is most likely to thrive, particularly those regions with strong technological infrastructure and policy support. The sectors most poised for agile manufacturing adoption include industries such as computer electronics, aerospace, and medical devices, in which the demand for highly customized products is growing rapidly.

Smaller firms and startups in Europe stand to benefit significantly from agile manufacturing's flexible, pay-per-use business models, which lower capital expenditures and mitigate risk. By offering these firms access to advanced manufacturing technologies without the need for heavy investments, agile manufacturing democratizes access to high-tech production capabilities.

In conclusion, agile manufacturing is a vital strategy for European manufacturers seeking to remain competitive in an increasingly complex and volatile market. Through its integration with advanced technologies, focus on sustainability, and adaptable approach to market demands, agile manufacturing enables European firms to respond swiftly to changing conditions, drive innovation, and enhance long-term success in the global marketplace.

1. Agile manufacturing and Industry 4.0 in Europe

The relevance of agile manufacturing in Europe has never been greater, driven by the need for resilient supply chains (Ahmed and Huma 2021), strategies that adapt to rapidly changing customer demands (Ahmed and Huma 2021), and the ability to respond to ongoing market trends in a constantly evolving environment (Maskell 2001). Additionally, Europe's manufacturing sector is becoming increasingly significant as consumers demand more specific, customized products. The shift away from mass production and the rise of shorter product life cycles (Maskell 2001) further highlight the value of agile manufacturing. This approach allows for the production of low-volume, high-quality, and customized goods, effectively catering to fragmented markets with more complex needs (Maskell 2001).

This growth is reflected by the fact that 34.4 million people are employed in the manufacturing sector across Europe, accounting for 27% of employment in the EU nonfinancial business economy (Westkämper and Walter 2014). SMEs, which are responsible for 45% of all manufacturing activities, play a crucial role in this ecosystem. This rise has been bolstered by long-term policies that support SMEs, thus laying a robust foundation for the widespread adoption of agile manufacturing (Mulhern, 1995).

Agile manufacturing is ideally suited to meet these evolving demands through a highly flexible system that can be rapidly adjusted as customer needs change (Maskell 2001). A core principle of agile manufacturing is the ability to deliver value, including service-rich products tailored to customer preferences. To achieve this, companies must be able to reconfigure their operations, which requires significant knowledge development within the organization. This internal innovation, supported by collaborative structures involving employees and external partnerships, allows agile manufacturing to adapt to unpredictable external conditions (Palani, Sathiya, and Palanisamy 2022).

The **Net-Zero Industry Act**, passed by the EU in April 2024, underscores the growing significance of agile manufacturing in Europe. This legislation aims to enhance manufacturing capacity in key sectors, particularly those focused on net-zero technologies, aligning agile manufacturing with the EU's goals of reducing energy consumption and minimizing waste (Council of the European Union 2024).

Agile manufacturing incorporates advanced manufacturing technologies and adaptable business models that vary in maturity. According to Swift and Booker (2013), each manufacturing process can be assessed based on economic factors, such as waste reduction, production rates, and material usage. Understanding these factors is essential for maximizing efficiency and cost-effectiveness in production. Furthermore, agile manufacturing's integration within the ongoing fourth industrial revolution, known as **Industry 4.0**, is key to understanding its broader impact. Industry 4.0, initially announced in 2011 as part of Germany's high-tech strategy, integrates **cyber-physical systems (CPS)** and **IoT** to enhance industrial ecosystems, extending physical operations into the virtual realm. This system manages global value chains while meeting growing customer demands for faster and more customized products (Li 2018).

Industry 4.0 represents a significant transformation in industrial processes. While Industry 3.0 was driven by computer capabilities, Industry 4.0 incorporates advanced technologies such as **artificial intelligence (AI)**, **big data**, **the internet of things (IoT)**, and **augmented reality (AR)** and is revolutionizing both production and services. These innovations increase the speed of product development and market entry while also facilitating automation through large-scale data processing. This represents a broader societal transition, as AI technologies enable better stakeholder models and more advanced knowledge integration into production (Spohrer 2024).

The EU's **Industry 4.0 plan** is instrumental in its adoption of agile manufacturing, ensuring that technological advancements, such as smart factories, cyber-physical systems, and decentralized self-organization, are integrated into European manufacturing (Li 2018).

2. General drivers of agile manufacturing

Agile manufacturing is increasingly becoming a cornerstone of Europe's manufacturing landscape, driven by the complexities of modern market demands and technological advancements. Several key drivers support its adoption, including heightened economic competition, market fragmentation, corporate cooperation, evolving consumer expectations, and growing social and environmental pressures (Larsen, Laursen, and Lassen 2023). Additionally, agile manufacturing is influenced by broader macroeconomic trends, such as sustainability, technological growth, supply chain risks, and the overall increase in manufacturing within Europe.

The continuous growth of European manufacturing is a major catalyst for agile manufacturing. SMEs contribute significantly to this growth, accounting for nearly 45% of manufacturing activity (Westkämper and Walter 2014). Strategic localization of manufacturing facilities, guided by geography, cost, and competence (Johansen and Winroth 2003), further supports the region's manufacturing expansion. **Localization strategies**, as emphasized by Witnthrow (2024), provide essential long-term benefits that align with the objectives of agile manufacturing in Europe.

2.1. Intensified competition

As competition in global markets intensifies, manufacturers face increased pressure to innovate and improve production efficiency. Agile manufacturing enables companies to respond quickly to market shifts, optimize production processes, and improve time to market, ensuring they stay competitive in this challenging landscape.

2.2. Fragmentation of mass markets

The traditional mass production model is now giving way to more fragmented markets in which consumers demand tailored and specific products. Agile manufacturing supports this transition by enabling low-volume, customized production. This flexibility allows manufacturers to respond quickly to diverse market demands.

2.3. Cooperative corporate networks

The rise of cooperative corporate networks across supply chains has become a key driver of agile manufacturing. Companies are increasingly collaborating to share resources and knowledge, and agile manufacturing provides the necessary flexibility to respond to changes in supply chain demands, fostering resilience and adaptability.

2.4. Evolving consumer expectations

As consumer expectations evolve, manufacturers are tasked with delivering more personalized products at competitive prices and faster turnaround times. Agile manufacturing enables rapid shifts in production to meet these demands, offering flexibility in product design and configuration.

2.5. Social and environmental pressures

The growing importance of sustainability and environmental responsibility has placed new pressure on manufacturers to adopt more sustainable practices. Agile manufacturing supports sustainability by optimizing resource use, reducing waste, and enhancing production efficiency, aligning with initiatives such as the **European Green Deal** and the **2050 sustainability goals**.

3. Macroeconomic drivers of agile manufacturing in Europe

In Europe, agile manufacturing is shaped not only by immediate market demands but also by significant macroeconomic factors. These broader influences include technological growth, sustainability goals, supply chain risks, deglobalization, and rising manufacturing activity in the region. Each of these factors plays a key role in shaping the landscape of agile manufacturing.

3.1. Technological growth and digitization

One of the foremost macroeconomic drivers is the rapid advancement in technology and digitization across Europe. The EU's **Digital Europe 2024 Strategy** emphasizes the integration of technologies such as big data, AI, and the IoT, all of which are critical for agile manufacturing systems. These technologies enable real-time adjustments, enhancing the flexibility and responsiveness of manufacturing processes.

Moreover, technological innovation allows manufacturers to mitigate risks by leveraging data analytics and predictive maintenance systems. This enables companies to foresee potential disruptions in the production process and address them proactively, thereby increasing production efficiency and resilience (Maskell 2001; Timmers 2022).

Industry 4.0 also plays a significant role in this transformation by introducing advanced digital models, such as CPS and IoT, extending the boundaries of manufacturing into virtual realms and enabling seamless integration across value chains.

3.2. Risk management in manufacturing

Agile manufacturing is highly effective in managing manufacturing risks, particularly those faced by European small and medium-sized enterprises (SMEs). According to Chiarini (2015), SMEs often encounter risks such as nonconforming products, supplier-related issues, and equipment failures. These risks can significantly impact production timelines and quality. However, agile manufacturing provides the flexibility and adaptability needed to address these challenges.

For example, by incorporating real-time monitoring systems and automation, agile manufacturing allows companies to quickly detect and rectify problems, minimizing downtime and ensuring the smooth operation of production processes. Furthermore, agile manufacturing systems help manufacturers adapt to supply chain risks, particularly those caused by external disruptions or fluctuations in supplier performance (Chiarini 2015).

3.3. Sustainability and policy drivers

Sustainability has emerged as a critical macroeconomic driver in European manufacturing, with both policymakers and consumers demanding more responsible and environmentally friendly practices. Agile manufacturing is well suited to address these concerns by enabling companies to optimize their resource use, reduce waste, and enhance overall production efficiency.

The European Union's 2050 Circular Economy Targets and the European Green Deal emphasize the importance of sustainable manufacturing practices. Agile manufacturing systems are aligned with these initiatives by promoting resource-efficient techniques that reduce material use and emissions. A notable example is the **H2 Green Steel Project**, which aims to cut carbon emissions in steel production by up to 95%, demonstrating how agile manufacturing can be integrated with sustainable technologies to achieve ambitious environmental goals (European Commission 2024).

Furthermore, policies such as **Horizon Europe** and the **Digital Decade Policy 2030** provide financial support for research and development in sustainable manufacturing. These policies encourage manufacturers to adopt innovative, environmentally friendly technologies and foster collaboration between governments, industries, and research institutions to drive green transformation (Timmers 2022).

3.4. Supply chain and manufacturing risk

In recent years, supply chain disruptions have become a significant challenge for manufacturers, particularly in light of global crises such as the COVID-19 pandemic. According to Feng *et al.* (2024), 81% of enterprises have experienced some form of supply chain disruption. Agile manufacturing helps mitigate these risks by localizing production and reducing reliance on complex global supply chains.

Technologies such as additive manufacturing further enhance this capability, allowing companies to produce parts on demand. This reduces the need for extensive inventories and minimizes the risk of obsolescence or delays caused by supply chain interruptions (Wu *et al. 2006*). By maintaining localized production capabilities, agile manufacturing systems enable manufacturers to continue operating efficiently, even in uncertain and volatile environments.

3.5. Deglobalization and geopolitical tensions

The rise of deglobalization, driven by protectionist measures, geopolitical tensions, and the need for strategic autonomy, has prompted European manufacturers to reassess their reliance on global supply chains. As global trade becomes more uncertain, manufacturers are shifting toward local production models to reduce their exposure to geopolitical risks.

Agile manufacturing technologies, particularly additive manufacturing, allow companies to produce goods closer to their end markets, thereby reducing the risks associated with long-distance supply chains. By localizing production, companies can respond more quickly to changes in trade policies, tariffs, or regulations. This flexibility is crucial in maintaining production continuity and ensuring resilience in a deglobalized world (Felbermayr 2024; Thomas and Gilbert 2014).

3.6. The growth of European manufacturing

Finally, the continuous growth of European manufacturing serves as a major macroeconomic driver for the adoption of agile manufacturing. The manufacturing sector remains a cornerstone of the European economy, employing 34.4 million people and accounting for 27% of employment in the nonfinancial business economy (Westkämper and Walter 2014).

SMEs, which constitute 45% of the region's manufacturing activity, are at the forefront of this growth. The EU's focus on long-term policies that support SME growth and innovation provides a favorable environment for the expansion of agile manufacturing. Additionally, the strategic location of manufacturing hubs, guided by factors such as geography, cost, and competence, enhances Europe's competitiveness on the global stage (Johansen and Winroth 2003).

3.7. Conclusion

The adoption of agile manufacturing in Europe is driven by a combination of technological, economic, and political factors. These macroeconomic drivers, ranging from technological growth and digitization to sustainability policies, supply chain risks, deglobalization, and rising manufacturing levels, underscore the importance of agility and flexibility in modern manufacturing. Supported by robust governmental policies and financial incentives, agile manufacturing is positioned to play a transformative role in the future of European industry, thereby ensuring competitiveness, sustainability, and resilience in an increasingly complex global environment.

4. Customer pain points

To fully grasp the significance of the rise of agile manufacturing, it is crucial to understand the key customer pain points that agile manufacturing systems address and to which they adapt.

The primary pain point relates to the challenges of creating customized products. Without agile manufacturing, customization options are limited, and manufacturers struggle to meet specific customer demands. This is compounded by a broader challenge faced by manufacturers: the need for advanced technological skills to continually improve their processes (Soldatos and Kyriazis 2021). As technologies within Industry 4.0 evolve rapidly, manufacturers often struggle to keep pace, particularly in addressing the rising demand for customization.

The degree of customization that a manufacturer can offer is often constrained by that manufacturer's production capabilities, competitive environment, and available technology. In addition, there are high threshold levels for providing customized products with quick turnarounds. Mass-customization strategies require the integration of elicitation, process flexibility, and logistics at the firm level (Mai *et al. 2016*).

Another pain point stems from the limited use of advanced cloud technologies, such as cloud manufacturing. Without integrating these technologies into production, traditional manufacturing processes fall behind agile systems in terms of evolution. Historically, solutions such as process tracking and machine communication have been geared toward traditional manufacturing and have lacked the advanced capabilities offered by cloud-based systems (Wang *et al. 2019*). This technological gap is a significant pain point for manufacturers. Cloud-based platforms can enhance manufacturing by collecting data during product usage, improving product design and allowing users to reconfigure designs according to specific needs (Wang *et al. 2019*). However, there are still areas that need improvement, including misaligned machine–cloud communication, limited cloud services, and minimal support for additive manufacturing (Wang *et al. 2019*).

A significant customer pain point is production time. Agile technologies, particularly additive manufacturing, enable significant time savings by being faster, more autonomous, and more reliable. These systems reduce changeover times between production runs and enhance overall production speed and quality. Most importantly, they improve time efficiency. For example, additive manufacturing is expected to become 50% cheaper and 400% faster in the coming 5 years (Attaran 2017).

Another key pain point is related to production and distribution planning within the supply chain, especially in the face of external uncertainties (Singh, Goyat, and Panwar 2022). Agile manufacturing addresses these challenges by leveraging technology to ensure the rapid flow of products across different channels. By incorporating intelligent data systems, agile manufacturing enhances reliability and transparency within supply chains (Singh *et al. 2022*). This is crucial, as technical barriers and a lack of transparency between supply chain members often result in inefficient production flows. The standardization of systems and open collaboration offer solutions to these issues (Singh *et al. 2022*).

A further pain point is the high capital investment required in traditional manufacturing systems. This financial barrier limits access to production experimentation, forcing customers to commit to purchasing expensive machinery. The future of agile manufacturing enables opportunities to create economic growth through enhanced productivity (World Economic Forum 2016). Agile manufacturing, with its digital and flexible business models, enables customers to experiment with production processes without making significant financial investments in machinery.

In Industry 4.0, manufacturers also face challenges in developing IT infrastructure and ensuring data security. Existing ICT infrastructures are often not scalable enough to support digital transformation, which complicates the adoption of agile manufacturing. However, advanced manufacturing technologies integrating IoT, cloud computing, and big data analytics offer solutions to these communication problems (Oliveira *et al. 2021*). AI and robotics play a key role here, with cobots (collaborative robots) facilitating safe and efficient interactions between humans and machines (World Economic Forum 2015).

Additionally, material waste is a major pain point, particularly in the context of the increasing demand for environmental sustainability. Autonomous production technologies can help reduce the material inputs necessary for production, aligning manufacturing practices with customer concerns about sustainability (Allgood and Kuepper 2024).

Supply chain management is another recurring pain point for manufacturers, driven by high-order cooperative relationships, the information revolution, and increasing customer demands. A study by the Supply Chain Forum identified the top three supply chain challenges as fragmentation, a lack of global project resources, and poor internal collaboration (Handfield and Steininger 2005). The complexity of modern supply chains, particularly the lack of synchronization between multiple intermediaries, can lead to inefficiencies. Agile manufacturing addresses these issues through automation and flexibility, allowing manufacturers to meet customer demands while reducing complexity.

Furthermore, a key pain point is the presence of regulation and compliance necessary for manufacturing production. This requires extensive know-how, which is a key offering of manufacturingas-a-service business models.

Lastly, the lack of centralized data systems is a significant pain point that hampers communication across supply chains (Handfield and Steininger 2005). Agile Manufacturing's incorporation of AI and cloud technologies helps solve this problem by centralizing data, improving information flow, and ensuring greater coordination along the supply chain.

In summary, the **key customer pain points** that agile manufacturing addresses include the following:

- Challenges in creating **customized products** due to limited production capabilities
- A **technological skills gap** among manufacturers in adapting to evolving technologies
- High thresholds for **mass customization**, requiring the integration of flexibility and logistics
- **Limited cloud technology** in traditional manufacturing processes
- **Production time inefficiencies**, with traditional systems being slower and less adaptable
- Difficulties in **production and distribution planning** due to external uncertainties in the supply chain
- **High capital investment** barriers, preventing experimentation without large financial commitments
- Insufficient **IT infrastructure and data security**, hindering full digital transformation
- **Material waste**, as manufacturers struggle to align with growing demands for environmental sustainability
- Fragmentation and lack of synchronization in **supply chain management**, leading to inefficiencies
- Regulation and compliance requirements, presents need for significant know-how capabilities
- A lack of **centralized data systems**, creating communication barriers within supply chains

5. Building blocks of agile manufacturing

Agile manufacturing is built upon several fundamental components that work together to create a responsive, adaptable, and highly efficient manufacturing environment. These core building blocks include agile process management, organizational agility, information systems, human–machine interaction, agile manufacturing technologies, and innovation in new business models. Together, they enable manufacturers to meet evolving customer demands, adapt to external uncertainties, and leverage cutting-edge technologies for a competitive edge.

5.1. Agile process management

Agile process management is a prerequisite for the success of agile manufacturing. It involves the recognition, analysis, and evaluation of trends affecting the manufacturing process, including macro, micro, mega, sociocultural, consumer, technological, and product trends. By managing these trends in real time, organizations can adapt to changes without predicting them. Key components within agile process management include IT systems, data analytics, smart sensors, communication networks, expanded reality, decentralized databases, AI, digital twins, and additive manufacturing (Birkel and Hartmann 2023).

Agile business process management (BPM) enables organizations to quickly adjust to dynamic external factors, enhancing strategy execution and process flexibility. Unlike traditional BPM, agile BPM incorporates speed, simplicity, and flexibility to meet organizational goals and respond to external events. By including employees in the process and leveraging their knowledge, organizations can develop new competencies, adapt to evolving customer demands, and deliver incremental improvements (Bernado Junior and de Padua 2022). Agile teams must be equipped with the right skills to achieve high performance and ensure a perfect fit with market demand (Poth *et al. 2021*).

5.2. Organizational agility

Organizational agility is a key prerequisite of agile manufacturing systems, providing a competitive advantage in environments characterized by volatility, uncertainty, complexity, and ambiguity. SMEs, in particular, benefit from agile strategies, as they often have fewer resources than larger enterprises, necessitating their ability to innovate quickly and efficiently (Pereira and Lopes Dias 2024). Agility in organizations involves streamlining business processes to achieve speed, accuracy, cost savings, and innovation, all of which are critical for maintaining a competitive advantage.

Agility also requires a group work design, which emphasizes the interdependence of team members in collective working models. The agile work environment supports a self-managed workforce, allowing employees to take ownership of tasks and improve customer orientation (Moore 2018). Agile organizations use frameworks such as Scrum to structure workflows, ensuring that teams can achieve specific goals, analyze outcomes, and adapt quickly.

5.3. Information systems

Agile information systems are the backbone of agile manufacturing, enabling seamless integration between different technologies and processes. Key technologies include cloud computing, big data, CPS, and simulations.

Cloud computing allows organizations to pool resources and scale rapidly, providing services such as cloud manufacturing, in which manufacturing capabilities are offered as a service (Alcacer and Cruz-

Machado 2018). Cloud manufacturing offers organizations cost savings by eliminating the need for extensive IT infrastructure and providing flexibility in manufacturing operations.

Big data plays a crucial role in providing insights into design, production, and maintenance processes. By analyzing structured and unstructured data, organizations can make better decisions, improve product quality control, and enhance equipment supervision.

A key component of agile manufacturing is the digital twin. The digital twin benefits production through providing this ubiquitous availability of data through sensor technology. CPS bridge the gap between digital and physical systems, allowing manufacturers to interact with the physical world through real-time data monitoring and virtual modeling. This creates opportunities for real-time management and optimized production strategies.

Simulations allow manufacturers to deal with complex and uncertain production environments by replicating operational systems and drawing inferences from artificial histories.

5.4. Human–machine interaction

Human–machine interaction is a critical aspect of agile manufacturing, as it optimizes collaboration between human operators and automated systems. In agile environments, humans and machines work together to enhance productivity and innovation.

Human–machine interaction is facilitated through cyber-physical human systems, which include feedback loops that allow for real-time adjustments in production processes (Jane, Ding, and Hernandez 2023). In Industry 4.0, humans act as operators, overseeing cloud computing technologies and managing various tasks, such as design, manufacturing, and logistics (Alcacer and Cruz-Machado 2018).

Technologies such as AR are increasingly used to enhance human performance by providing real-time information that aids task execution. Operators use AR manuals, augmented interfaces, and head-up displays to streamline the production process and improve accuracy (Alcacer and Cruz-Machado 2018).

The rise of cobots has further enhanced human–machine collaboration by enabling flexible product development, manufacturing, and assembly. Cobots are designed to work safely alongside human operators, improving affordability and flexibility in manufacturing processes (Alcacer and Cruz-Machado 2018).

5.5. Agile manufacturing technologies

Agile manufacturing technologies form the foundation of modern manufacturing systems and enable flexibility, efficiency, and innovation. The two key technologies driving agile manufacturing are additive manufacturing and laser material processing.

Additive manufacturing (AM), also known as 3D printing, is a transformative technology in agile manufacturing. AM allows for the creation of objects from 3D data using materials such as liquid, powder, or sheet metals (Kleer and Piller 2019). This technology provides users with production capabilities that they would otherwise lack, thus encouraging user innovation. AM facilitates prototyping, trial and error, and customization, making it a flexible system that meets the needs of Industry 4.0.

Laser materials processing is another core agile manufacturing technology used for cutting, joining, machining, and rapid prototyping. As a subtractive manufacturing method, laser cutting uses high-powered electromagnetic radiation to shape materials, allowing for high productivity, automation, and reduced operating costs (Manna and Majudamar 2003). The versatility of laser processing makes it essential for various industries, particularly those requiring precision and efficiency in material handling.

5.6. Innovating new business models

A key component of agile manufacturing is the evolution of business models to align with rapid changes in technology and the external environment. As businesses shift from traditional transactional models to pay-per-use models, manufacturers gain increased agility and speed in adopting new technologies. This business model innovation is vital for ensuring flexibility, scalability, and responsiveness in production.

The success of an agile business model is linked to its ability to adapt to environmental changes and align organizational models with business needs. An agile solution should focus on the strategic management of expenditures, cutting-edge technological implementation, and employee involvement while also ensuring that the procurement function is integrated into product development (Nicoletti 2018). These new models enable manufacturers to reduce capital investment costs, as businesses pay only for the resources they use, providing the flexibility to scale operations as market demands evolve.

Another aspect of innovation in business models is the collaborative vendor networking approach. This trend emphasizes automated negotiations, high-speed transactions, and the development of long-term, value-adding relationships between manufacturers and vendors. By fostering collaboration, companies can ensure that their procurement processes are aligned with agile manufacturing goals. The success of these models often depends on the centralization or decentralization of procurement activities and the integration of tools such as big data analytics and automated processes into the decision-making process.

Product innovation and process innovation play key roles in this evolution. Product innovation enables employees to make optimal supply decisions with approved models, while process innovation leverages technologies such as big data and automation to optimize internal workflows. By improving the inflow and outflow of information, agile business models enhance internal innovation capabilities and expand markets, driving growth and competitiveness (Nicoletti 2018).

Finally, digital business models are transforming into change agents by enabling value creation and promoting flexibility in manufacturing. These models rely on digital tools to streamline production, increase responsiveness, and enable the rapid adoption of new technologies, ensuring that manufacturers stay ahead in an increasingly competitive global market.

6. The make-or-buy decision-making model in agile manufacturing

The decision-making process for manufacturers when it comes to producing components or products generally follows two traditional paths: to make the parts in-house or to buy the parts from an external supplier. Each option comes with its advantages and challenges, influencing factors such as cost, control, time to market, and risk. However, with the introduction of agile manufacturing, a third alternative is now emerging: to make parts in a more agile and flexible way without significant capital investment and with reduced training needs and faster setup—this is the evolving "pay-per-use" business model in agile manufacturing.

The model can be broken down into three fundamental paths:

- **Make (traditional approach)**: Companies invest in the machinery and infrastructure required to produce the parts themselves. This decision typically involves high upfront capital expenditure but provides greater control over quality and production processes.
- **Buy**: Companies outsource production to third-party suppliers, leveraging their capabilities and avoiding the costs of in-house production. This approach is often favored when demand is inconsistent or the capabilities required are beyond what the company can handle internally.
- **Use technology** (agile manufacturing): This is a new model made possible by agile manufacturing systems, which provide companies with the ability to produce in-house with flexibility, minimized capital expenditure, and rapid time-to-market advantages. Companies can adopt an agile process, leveraging technologies such as cloud manufacturing and additive manufacturing without heavy investments in capital equipment or labor training.

6.1 Make or buy: a traditional decision model

The traditional make-or-buy decision is first and foremost when evaluating manufacturing strategies. Companies must assess whether they want to produce in-house or outsource to external suppliers. Each decision brings trade-offs regarding control, cost, quality, and flexibility.

As presented in the diagram below, the core factors influencing make-or-buy decisions involve capital investment, control over production, and the ability to manage risk internally.

Please see **Exhibits 1** for a detailed comparison of make vs. buy considerations

- **Make**: This requires higher capital investment but provides greater control over production quality as well as flexibility. The ability to mitigate risk in-house is key.
  - **Capital intensive**: Significant upfront investment in technology, equipment, and skilled labor is required.
  - **Control**: This provides full oversight of production, ensuring quality and flexibility in adapting to new market demands.
  - **Risk:** Risk mitigation is internalized, and the company retains full ownership of production, which can be beneficial in certain high-risk sectors, such as aerospace (Goehlich, R. 2009).

- **Buy**: This requires lower upfront costs by outsourcing production to suppliers, but it means less control over processes and potential reliance on external partners.
  - **Lower capital expenditure**: Outsourcing eliminates the need for expensive machinery and associated operational costs.
  - **Efficiency:** This is ideal for situations in which demand is inconsistent, seasonal, or project-based. Companies can focus on their core competencies while outsourcing noncore activities.

6.2 The evolving agile manufacturing model: a third path

Agile manufacturing introduces a new decision-making element that shifts the traditional make-or-buy dichotomy. With agile systems, companies can make with much greater flexibility by utilizing cloud-based, pay-per-use models for production without the need for large capital investments.

The following are among the key factors in an agile "make" decision:

- **Reduced capital investment**: Agile manufacturing technologies offer a pay-per-use model that minimizes the need for costly capital expenditure (CapEx) investments. Companies can access high-end manufacturing technologies without purchasing machinery outright.
- **Speed and flexibility**: Agile processes reduce the time needed to bring new products to market, allowing companies to remain competitive even when demand shifts rapidly.
- **Risk mitigation**: By utilizing agile systems, companies can experiment with new products and processes with minimal risk. If demand fluctuates, they can scale production up or down without being locked into long-term investments.
- **Short lead times**: Agile technologies such as additive manufacturing enable much shorter lead times for production, reducing the time to market for customized and small-batch products.
- **Project-based demand**: Agile manufacturing allows manufacturers to meet short-term or seasonal demand spikes without needing to purchase new equipment. Companies can scale production as needed for the duration of the project, ensuring flexibility and cost-effectiveness.
- **Regulation and compliance**: Agile manufacturing offers a advanced know-how capabilities to navigate the present complications of regulation and compliance demands.

See **Exhibit 2** to visualize the factors influencing the adoption or non-adoption of an agile manufacturing business model and a comparison of the contributing factors.

6.3 Core considerations for agile manufacturing decisions

As manufacturers weigh the option of adopting agile manufacturing, several core factors emerge in the decision-making process:

- **Short lead times**: Companies that need rapid turnaround times may find the agile pay-per-use model more favorable than traditional manufacturing processes.
- **Experimentation and innovation**: Agile systems allow companies to experiment with new designs and production processes without heavy capital investment, enabling innovation without long-term risk.

- **Demand seasonality:** If demand fluctuates seasonally, an agile model allows companies to avoid the high costs of maintaining underutilized equipment by paying only for what they need when they need it.
- **In-house capabilities:** For companies that already have strong internal teams trained in cloud operations or have well-established IT infrastructures,the agile manufacturing model can improve these capabilities. However, for those without these capabilities, agile manufacturing offers a plug-and-play solution that eliminates the need for extensive internal training and development.

6.4 Risk and financial considerations

Another critical element in the make-or-buy decision is the financial risk and capital expenditure involved. The traditional decision to make involves substantial upfront costs and potential risks if the technology becomes obsolete. On the other hand, agile manufacturing allows for financial flexibility, because companies can scale their production based on real-time demand without tying up capital in equipment purchases.

For companies concerned about the resale value of machinery, agile manufacturing offers a lower-risk alternative because it avoids the risk of depreciating assets. The pay-per-use model allows companies to remain nimble and adjust to changing market conditions without being locked into expensive long-term investments.

According to a 2015 analysis by the Boston Consulting Group (BCG), external factors, such as currency fluctuations, energy costs, rising wages, and the advent of advanced manufacturing technologies, have made the make-or-buy decision even more crucial. BCG highlighted that companies need to adapt to dynamic economic conditions, and strategic decisions must balance cost structure, flexibility, and control over production. The BCG analysis showed that the strategic value and cost structure of each decision can have profound long-term effects on a company’s operational capabilities and competitiveness.

6.5 Innovating new business models

Finally, business model evolution is a key component of agile manufacturing. Innovation is essential for a successful agile business model, as it is linked to changes in the environment, the core influencer of the need for flexibility in an organization.

An agile solution should align the organizational model with business needs, manage expenditures strategically, implement cutting-edge solutions, and focus on employees while involving the procurement function in product development. Collaboration with vendors through automated negotiation and long-term value-adding relationships is another dependency, leading to high flexibility and responsiveness to market needs.

7. Business models in agile manufacturing

Agile manufacturing presents a new paradigm in business models whereby traditional production methods are redefined by flexibility, technology integration, and pay-per-use systems. This chapter explores how these innovative business models compare with existing models, their structure, and their potential to transform manufacturing as a service, similar to the digital transformation seen in other sectors. This evolving landscape leverages Industry 4.0 technologies to reimagine the ways companies produce and deliver value.

7.1 Business model foundations in agile manufacturing

Business models in agile manufacturing are built around three core components: **value proposition**, **value creation**, and **value capture**. These components are driven by technological innovation, enabling organizations to adapt to the dynamic needs of markets under the influence of Industry 4.0. The digitization of business processes offers a sustainable competitive advantage, allowing manufacturers to remain agile, productive, and competitive in increasingly volatile markets (Günther Schuh *et al. 2021*).

In a digital business model, technological enablers, such as data analytics, cloud platforms, and smart sensors, allow for the restructuring of value chains to improve operational performance. Such a business model not only boosts SME productivity but also fosters information sharing and collaboration across various industries (Kazantsev and Martens 2021). Additionally, the combination of physical products and digital services strengthens customer relationships and offers greater flexibility and long-term engagement (Jussen 2021).

7.2 Pay-per-use and manufacturing-as-a-service

One of the most transformative shifts in agile manufacturing is the adoption of a pay-per-use model, often referred to as manufacturing-technology-as-a-service. This model allows manufacturers to access advanced technologies without the need for significant capital investment in equipment. By paying only for what they use, companies can minimize their financial risk while benefiting from the flexibility to scale production according to demand.

The pay-per-use model in agile manufacturing mirrors other service-based models, such as platform-as-a-service or product-as-a-service, where users only pay for resources consumed. This model enables manufacturers to:

- **Mitigate financial risks**: Instead of investing in expensive equipment that may become obsolete, companies can "rent" production capacity based on current project needs.
- **Improve scalability**: Businesses can adjust production volumes quickly and efficiently, which is particularly useful for SMEs or startups facing fluctuating demand.
- **Experiment with new technologies**: Companies can adopt additive manufacturing, cloud-based production, or laser cutting on a trial basis, iterating without long-term commitment (Mathias Zink *et al*. 2021).

7.3 Manufacturing as a service and servitization

Manufacturing as a Service (MaaS) integrates servitization into its business model, where value is created through the addition of services to traditional products. These services range from maintenance and support to process simulation and optimization. MaaS allows for better alignment with customer needs, focusing on solving specific customer problems and offering tailored solutions.

- **Product-oriented services**: Include support services, such as maintenance or installation, that complement the physical product.
- **Process-oriented services**: Focus on optimization and simulation, helping customers improve efficiency without owning the physical infrastructure (Szasz et al. 2017).

The servitization strategy is particularly relevant for agile manufacturing, as it allows companies to offer a complete service package without requiring the customer to own the machinery. This enables access to industrial-grade production technology for a broader range of customers, thereby reducing barriers to entry (von See, Grafe, Lodemann, S., and Kersten 2021).

7.4 Comparisons with platform-as-a-service and product-as-a-service

Agile manufacturing shares many similarities with other service-oriented models, such as platform-as-a-service and product-as-a-service. Both models emphasize flexibility, scalability, and reduced capital expenditure.

- **Platform-as-a-service:**
  - Provides a cloud-based platform that allows users to build, test, run, and scale applications without owning the underlying hardware or software infrastructure.
  - Enables faster time to market, shorter lead times, and cost-effective scalability, which are core characteristics shared by agile manufacturing systems (IBM 2024).
- **Product-as-a-service**
  - Focuses on selling products along with value-added services, such as maintenance and lifecycle management. The customer pays for the service rather than the product itself, making this model highly suitable for smaller companies that cannot afford large capital investments in machinery.
  - Agile manufacturing follows a similar path by enabling businesses to access manufacturing technologies on demand and reducing the need for heavy upfront investment (Kesavapanikkar *et al*. 2023).

7.5 Technology-as-a-service in agile manufacturing

The technology-as-a-service (TaaS) model leverages innovations such as cloud computing, AI, and the IoT to transform how companies access and utilize manufacturing technology. It reduces traditional cost structures by automating processes and providing real-time data for decision-making.

- **Flexibility and automation:** The integration of AI and cloud-based solutions enables manufacturers to automate complex tasks, improve decision-making, and reduce operating costs.
- **Renewable revenue streams**: The TaaS model fosters long-term customer relationships by allowing companies to pay only for the services they use. This setup aligns perfectly with the goals of agile manufacturing, whereby flexibility, adaptability, and innovation are key (Lah and Wood 2016).

7.6 Benefits and core competencies of agile manufacturing

Agile manufacturing's new business models offer several key benefits, including the following:

- **Reduced production costs**: Technologies such as additive manufacturing and cloud manufacturing lower fixed costs, making localized production more viable and cost-efficient (Kleer and Piller 2019).
- **Process innovation**: Agile systems enable rapid product development, optimize supply chains, and foster creative solutions (Ukobitz 2020).
- **Customization and adaptability**: Agile manufacturing allows companies to respond quickly to changing customer demands and market conditions by offering customized goods through flexible, localized production systems (Potdar *et al*. 2017).

7.7 Dependencies and constraints in agile manufacturing

Agile manufacturing depends on several key factors for successful implementation and sustainability. However, it also faces several constraints, particularly from global competition, technological investment, and workforce readiness.

7.7.1 Dependencies

- **Educational institutions**
  A core dependency of agile manufacturing is the role of educational institutions in fostering innovation and preparing a skilled workforce. These institutions promote research, develop future employees, and serve as innovation hubs through on-campus labs that experiment with smart factory technologies, cloud computing, and AI-based systems (Gartner 2021). By partnering with manufacturers, they enhance real-world application and training opportunities, making sure the labor market is equipped with the skills necessary for agile manufacturing's growth and adoption.
- **Enterprise networks**
  Agile manufacturing systems depend heavily on enterprise networks, particularly an interconnected system of original equipment manufacturers (OEMs) and contract manufacturers. These networks facilitate the sharing of resources, knowledge, and tools essential for responding quickly to customer demands. Collaboration among suppliers, manufacturers, and customers forms a dynamic network that allows agile manufacturers to adjust rapidly to market changes (Koh and Wang 2010). This interlinked system ensures that the manufacturing process remains adaptable and efficient, creating competitive advantages in terms of cost savings and lead times.
- **Technological infrastructure**
  The infrastructure supporting agile manufacturing includes cloud platforms, AI-driven systems, and IoT technologies, which play a critical role in making the system agile. These technologies facilitate real-time data collection, automated processes, and advanced analytics, which are necessary for the agility and adaptability of manufacturing systems. Without these technological innovations, agile manufacturing would not be able to offer the benefits of rapid prototyping, quick customization, and efficient production.

7.7.2 Constraints

- **Global competition**
  One of the most significant constraints in adopting agile manufacturing is global competition. For example, **China's Made in 2025 initiative** presents a serious challenge to European agile manufacturers. The initiative focuses on increasing China's innovation-driven manufacturing capabilities, making it a formidable competitor in advanced technologies such as AI, cloud platforms, and robotics (Li 2018). North America is another major competitor, with the National Network for Manufacturing Innovation in the U.S. driving advancements in lightweight metals, automated manufacturing systems, and digital innovation (Babel 2022). These competitors are driving innovation at a rapid pace, pressuring European manufacturers to continuously innovate and evolve.

- **Supply chain constraints**
  Agile manufacturing's dependence on global supply chains can also be a limiting factor. The reliance on raw materials and components from global suppliers creates vulnerabilities, especially when supply chains are disrupted by geopolitical events, trade restrictions, or environmental crises. Such disruptions hinder the agility of manufacturers, preventing them from responding quickly to changes in demand or production requirements (Koh and Wang 2010).

- **Technological investment and workforce readiness**
  The adoption of agile manufacturing systems requires significant technological investments in cloud infrastructure, AI systems, and IoT platforms. For SMEs, the high cost of these technologies can act as a deterrent, especially in industries in which profit margins are thin. Moreover, the lack of a skilled workforce trained to operate these advanced technologies can also limit the scalability of agile manufacturing. Companies that do not have infrastructure or trained personnel in place may struggle to implement and maintain agile systems.

7.8 Conclusion

Agile manufacturing's business models—particularly pay-per-use, manufacturing-as-a-service, and technology-as-a-service—represent a fundamental shift in how companies approach production. These models reduce capital investment risks, offer scalable solutions, and foster a more collaborative, service-driven manufacturing ecosystem. By integrating cloud computing, AI, and data analytics, agile manufacturing enables companies to remain competitive, adaptable, and innovative in a rapidly changing global landscape.

8. Manufacturing technologies for agile manufacturing

Agile manufacturing thrives on technologies that prioritize flexibility, ease of setup, and fast adaptability to new designs, all while reducing CapEx. The challenge lies in selecting technologies that align with agile manufacturing principles such as reduced setup time, minimal training requirements, and seamless human–machine interaction through the integration of AI.

While all manufacturing technologies are adaptable to this approach,some technologies are considered to be early adopters, while other technologies require further development. The technologies most aligned with agile manufacturing are those that allow rapid prototyping, customized production, and leaner processes, thereby reducing production and logistics complexities. Among the most promising **are AM and laser cutting** technologies, which not only embody the principles of agility but also offer significant potential in reshaping industries through more costeffective and customizable production processes.

8.1 3D printing as a core agile manufacturing technology

AM, widely known as 3D printing, is one of the most important technologies enabling agile manufacturing. It directly responds to customer demands for rapid prototyping and highly customizable products while reducing waste. Through AM, manufacturers can prototype faster, produce customized components, and avoid the high CapEx investments associated with traditional manufacturing.

3D printing enables agile manufacturing in several ways:

- **Rapid prototyping**: AM allows fast iteration of designs, enabling manufacturers to prototype and test products in real time. This eliminates long production delays and aligns perfectly with the demand for short lead times, which are central to agile methodologies
- **Flexibility**: AM allows manufacturers to produce highly complex parts in a single production run, eliminating the need for multiple suppliers and reducing transport costs (Thomas and Gilbert 2014). With 3D printing, companies can create complex geometries and assemble components on demand, bypassing the logistical constraints of traditional methods (see **Exhibit 3** for a comparison of traditional vs. agile manufacturing).
- **Customization**: The ability to tailor products to specific customer requirements is a hallmark of 3D printing. This flexibility aligns directly with the goals of agile manufacturing, allowing manufacturers to provide customized goods while minimizing waste and inventory costs (Mai, Zhang, Tao, and Ren 2016).

The following are key techniques in additive manufacturing:

- **Vat polymerization**: Using photopolymerization techniques, a liquid resin is hardened layer by layer to create detailed and precise components (Shivananda Devi and Nilanjana 2022).
- **Material jetting**: This technique allows highly detailed models to be built by selectively depositing material layer by layer using ultraviolet light for curing (Alcacer and Cruz-Machado 2018).
- **Powder bed fusion**: This technique uses lasers to selectively melt layers of powder to create finished parts. It is especially beneficial for producing parts with complex geometries from a variety of materials, such as metals, polymers, and ceramics (Gibson, Rosen, Stucker, and Khorasani 2021).
- **Fused deposition modeling (FDM):** One of the most cost-effective AM methods, it uses a continuous filament fed from a spool, making it particularly suited to industries needing affordable, scalable, and flexible production (Jyeniskhan et al. 2024). See **Exhibit 4** for a detailed ranking of the factors affecting FDM technology.

8.2 Laser cutting: precision and flexibility in agile manufacturing

Laser cutting technology, which works using highly focused beams of light to cut through various materials, offers substantial flexibility, precision, and speed—critical factors for agile manufacturing. This technology is ideal for industries that require precision machining and customization, such as the electronics, aerospace, and automotive sectors.

- **High precision**: Laser cutting allows for extremely accurate cuts with minimal waste, making it ideal for customized manufacturing. It is also well suited for flexible production environments where varying product designs need to be implemented quickly and with minimal tooling costs (Manna and Majudamar 2003).
- **Ease of setup**: Unlike some traditional manufacturing methods, laser cutting is easy to set up and does not require extensive operator training, making it an attractive option for agile processes in which quick transitions between jobs are necessary.
- **Reduced setup time and costs**: Laser cutting can be set up rapidly with minimal overhead, aligning well with the agile manufacturing model that emphasizes low CapEx and quick adaptability (Ready, 1997).

8.3 Other manufacturing technologies: adaptability to agile manufacturing

While AM and laser cutting are prime examples of technologies ideally suited to agile manufacturing, other existing manufacturing methods, such as injection molding, die casting, and metal injection molding (MIM), are not inherently agile but can be adapted. These technologies require redesign or significant modification to fit within an agile model due to their high CapEx requirements, long setup times, and the specialized knowledge needed to operate them. They include the following:

- **Injection Molding:** As one of the more complex processes in traditional manufacturing, injection molding involves creating molds from materials such as aluminum and plastics, which have varying levels of fixed costs and duration. To make injection molding more agile, manufacturers must focus on optimizing setup times, reconfigurability, and adaptability. As explained by Professor Joaquim Minguella Canela in an interview (Personal Communication, September 2, 2024), "For a manufacturing technology to be agile, it must include fast response, adaptability, reconfigurability, robustness, knowledge transfer, cooperativity, and universality." This demonstrates the need for injection molding technology to evolve with an agile framework, whereby flexibility in materials, faster breakeven points, and lower CapEx are essential to success in various production environments.
- **Metal injection molding:** MIM allows for high precision and complexity in part production but involves high upfront costs, making it less suitable for companies looking to implement agile practices immediately (Shin Zu Shing Co. Ltd. 2016). For MIM to become agile, it would need redesigning to reduce setup costs and allow for easier scalability. See **Exhibit 5** for a comparative analysis of MIM characteristics.
- **Die-casting:** Commonly used in automotive manufacturing, die-casting can produce large quantities of metal parts but lacks the flexibility required by agile systems. Although it is fast and precise, it requires extensive upfront investment in molds and is less adaptive to rapid changes in production (Gupta 2009).

This analysis of technologies such as injection molding highlights the challenges of adopting these processes within an agile framework. As Professor Minguella Canela pointed out, "The breakeven point contributes to a manufacturing technology's ability to be adopted or not as agile, as firms will inevitably benefit from cost effectiveness in manufacturing production." The need to consider factors such as adaptability, reconfigurability, and knowledge transfer is crucial in determining how traditional manufacturing technologies can be transformed to fit into agile manufacturing practices.

Other manufacturing technologies include the following:

- **Thermomechanical Processing**: This process combines mechanical deformation with thermal treatment, optimizing the properties of metals and making it suitable for industries such as aerospace and automotive. However, its complexity and high CapEx requirements limit its immediate applicability in agile manufacturing. However, it can play a role in agile production if modified for faster setup and easier reconfigurability. The ability to use this technology to fine-tune the properties of metals makes it suitable for scenarios requiring high strength-to-weight ratios, which are critical in industries such as automotive (Jeyaprakash and Yang 2020).
- **Computer numerical control (CNC)**: CNC machining has long been a staple in manufacturing for its precision and automation capabilities. It represents subtractive manufacturing, in which material is removed to create a final part. While CNC is not inherently agile due to its dependence on rigid setups and specialized tools, it can become part of an agile system through improved software integration, AI, and automation, enabling faster setup, remote operation, and flexible production. The incorporation of CNC into agile systems will likely require seamless interaction with AI and cloud platforms, reducing operator training needs and setup times (Davim 2019).
- **Subtractive manufacturing**: Techniques such as lathing and milling are commonly used in traditional setups. These processes are excellent for high-precision tasks but involve significant material waste. For these methods to be adopted in agile systems, the focus would have to be on reducing setup time and ensuring rapid transitions between jobs (Davim 2019). See **Exhibit 10** for information regarding the flexibility of laser-cutting technology, a core subtractive manufacturing technology.
- **Photolithography**: Widely used in the production of semiconductors and microelectronics, photolithography excels at creating high-precision patterns on surfaces. However, its rigid processes and specialized materials limit its flexibility. Over time, there could be innovations to make it more agile by incorporating modular setups and automation, but currently, it remains a more rigid and specialized technology for specific industries, such as electronics (DeSilva 2014).

8.4 Criteria for agile manufacturing technology adoption

For a technology to be considered truly agile, it must meet several criteria:

- **Ease of setup**: Agile technologies should be quick to set up and require minimal downtime between transitions.
- **Minimal training requirements**: Agile technologies should be easy to operate with minimal training to allow for rapid deployment across multiple locations.
- **Flexibility**: Agile technologies should be adaptable to various manufacturing environments and capable of producing a range of product designs without major modifications.
- **Low CapEx**: Agile technologies should not require significant capital investments, allowing companies to adopt them without incurring heavy costs.
- **Transportability**: Agile technologies should be easy to transport and set up at new locations, allowing manufacturers to move production closer to demand, as required by modern supply chains. See **Exhibit 7** for a breakdown of the components influencing adoption of agile manufacturing technologies.

8.5 Additional technologies worth mentioning

- **Thermomechanical Processing**: Thermomechanical processing is essential for high-performance materials. It allows for precise control of a material's microstructure through heat and mechanical work. For example, this process is crucial in industries such as aerospace and automotive, for which high-performance materials are required. Thermomechanical processes could potentially be adapted to agile systems by focusing on modularity, but their reliance on complex infrastructure limits their immediate inclusion in agile frameworks (Jeyaprakash and Yang 2020).
- **Photolithography**: As discussed, photolithography plays a vital role in semiconductor manufacturing, but it is less aligned with agile manufacturing due to its precision but also due to its high complexity and cost (DeSilva 2014). It will likely not become a significant player in the agile space without further innovation to simplify and scale its processes.
- **Laser beam machining**: This method is frequently used in high-precision industries to cut materials with great accuracy using laser beams. The ability to apply laser beams to intricate designs without the need to switch tools makes it compatible with agile manufacturing. However, high power consumption and the need for specialized environments mean that laser machining is more suited to advanced agile systems that have already integrated significant automation and machine-learning capabilities (Swift and Booker 2013).
- **Material joining (hybrid structures)**: Combining different materials, such as aluminum and steel, can optimize performance while reducing weight. Joining technologies that weld different materials together, such as laser beam welding, are increasingly important in industries such as automotive, for which lightweight designs are critical. This process can become agile if modular machines capable of performing multimaterial joining are developed (Mathieu *et al*. 2005).

8.6 Materials in agile manufacturing

The materials used in agile manufacturing are a crucial factor in determining the feasibility and efficiency of various technologies. Trade values for plastics, metals, and machine parts related to additive manufacturing are covered in **Exhibits 8**, **9** and **10** respectively.

Agile manufacturing reduces material usage, using technologies such as additive manufacturing and laser processing techniques. Through producing in smaller batches in a more adaptable manner, there is less opportunity for wasted production than in large batches. An analysis showed that material costs represent between 27.1% and 30.4% of the price per part, while machine costs account for 58.7% to 65.9% (Thomas and Gilbert 2014).

8.7 Looking ahead: addressable market potential for agile manufacturing technologies

The potential market for AM and laser cutting in agile manufacturing is vast. These technologies are becoming increasingly important in industries such as aerospace, healthcare, and electronics, for which customization, fast time to market, and flexible production are key to success. The addressable market will be explored in greater detail in another chapter.

In conclusion, while many traditional manufacturing technologies can be adapted over time to fit within an agile framework, the immediate future of agile manufacturing lies in flexible, digitalized technologies, such as 3D printing and laser cutting. These technologies embody the agility, low CapEx, and scalability that define the agile manufacturing model, setting the stage for more widespread adoption in the years to come.

Exhibit references

- **Exhibit 4:** Factors affecting fused deposition modeling technology. See how the two components of the ease of printing and cost as highly ranked facets of the technology.
- **Exhibit 5**: Characteristics of metal injection molding. See the two components of product complexity and total cost represented as benefits of this technology.
- **Exhibit 6**: Manufacturing technologies adopted in agile manufacturing system and adoptability scorecard.
- **Exhibit 3:** Comparison of traditional vs. agile manufacturing.
- **Exhibit 7:** Components influencing agile manufacturing technology adoption.

9. Potential adopters of agile manufacturing

Agile manufacturing technologies are ideal for a variety of manufacturing customers, including manufacturers of interim products, contract manufacturers, OEMs, hardware startups, and firms engaged in outsourcing. Each group has unique challenges and opportunities regarding the adoption of agile manufacturing technologies.

9.1 Manufacturers of interim products and contract manufacturers

Manufacturers of interim products, also referred to as contract manufacturers, play a crucial role in the supply chain by producing parts essential for the final assembly of products. These manufacturers typically partner with OEMs but often lack direct access to end customers. By adopting agile manufacturing and digital business models, they can gain key advantages, such as the following:

- **Faster market access and scalability:** Agile systems enable manufacturers to quickly scale production and respond to fluctuating demand, offering shorter lead times and greater flexibility.
- **Product improvement:** Real-time data collection allows for ongoing improvements in product quality and process optimization.
- **New knowledge creation:** The data accumulated during production enable the generation of insights that contribute to new product development and innovation (Jussen 2021).

By leveraging service-oriented business models, these manufacturers can use agile cloud architecture to provide direct services, reduce dependence on OEM customers, and establish stronger relationships with their own customers (Jussen 2021).

9.2 OEMs

OEMs produce parts and components in-house for use in their own products or those of other companies. These manufacturers face different challenges from contract manufacturers but can still benefit from adopting agile manufacturing technologies.

- **Control over production:** By producing components in-house, OEMs maintain greater control over their production processes, ensuring that quality and proprietary technology remain within the company.
- **Cost considerations:** OEMs typically have higher initial capital costs due to owning their production facilities, but agile technologies, such as flexible, AI-driven machines, can reduce overall operational costs and improve efficiency.
- **Faster time to market:** Agile manufacturing technologies allow OEMs to quickly adapt to market changes, meet customized demand, and reduce lead times in launching new products (Larsen *et al*. 2023).

9.3 Hardware startups

Hardware startups, which focus on designing and developing physical products, such as IoT devices and industrial applications, are increasingly adopting agile manufacturing technologies. Several factors drive this trend:

- **Lower entry threshold:** Agile manufacturing technologies such as 3D printing have made it easier for hardware startups to produce small batches and prototypes with minimal capital investment (Sefton, Rönkkö, and Bellgran 2020).
- **Flexibility and scalability:** Agile systems offer these startups the flexibility to scale production quickly without the need for significant upfront investment in manufacturing infrastructure.
- **Production competence:** Many hardware startups rely on external manufacturers for production due to a lack of in-house expertise. Agile manufacturing provides them with a more reliable and efficient alternative to production (Sefton *et al*. 2020).

9.4 Outsourcers

Outsourcers, or firms that delegate noncore production activities to external manufacturers, are also ideal candidates for adopting agile manufacturing technologies. In today's dynamic and competitive business environment, outsourcing is a way for companies to remain flexible and quickly adapt to external changes (Khalatur, Kuprina, and Kurbatska 2021). Agile manufacturing offers the following benefits to outsourcers:

- **Cost efficiency:** Outsourcing noncore processes through agile systems helps firms reduce operational costs while maintaining flexibility.
- **Faster innovation cycles:** Agile manufacturing reduces the time to market for innovations, enabling faster product development and scaling (Khalatur et al. 2021).

10. Total addressable market for agile manufacturing in Europe

To accurately estimate the total addressable market for agile manufacturing in Europe, it is essential to look at key manufacturing activities, industrial sectors, and geographic regions that have the potential to adopt these technologies.

10.1 Manufacturing activities in Europe

The top five manufacturing activities by value of production in the EU from 2013 to 2023 included motor vehicles, machinery equipment, food products, fabricated metal products, and chemicals (European Commission 2024). These industries collectively represent a significant portion of the addressable market for agile manufacturing, especially as they are capital intensive and could benefit from the flexible, scalable, and cost-efficient nature of agile manufacturing technologies.

10.2 European industrial sizing

European industrial sizing is consistently representative of market potential for agile manufacturing adoption. (See **Exhibits 11** to **14** for an industry breakdown, the value of manufacturing enterprises, trade data on European machinery, and financial data on European industrial companies.) See **Exhibit 15** for data on the 3D printing material market. See **Exhibit 16** for data on the rubber and plastics market. See **Exhibit 17** for a synthesis of manufacturing technologies used in the construction industry.

10.3 Outsourced technology manufacturing services

Agile manufacturing also presents significant growth potential in the outsourced technology manufacturing services sector. The increasing demand for AI-driven and IoT-integrated manufacturing solutions suggests that contract manufacturers and OEMs may seek to adopt agile manufacturing to keep up with trends in efficiency and productivity (MarketLine 2018). (See **Exhibits 18** and **19** for outsourced manufacturing data.)

10.4 Hardware and electronics manufacturing

The European hardware and IT hardware market presents a further opportunity for agile manufacturing, with key sectors, such as semiconductors, OEMs, and original design manufacturing, seeing strong growth due to the integration of AI, cloud platforms, and additive manufacturing. The **Digital Decade Policy Program** is expected to drive further expansion in these areas (MarketLine 2023). (See **Exhibits 20** and **21** for hardware market data.)

10.5 Sector-specific sizing

- **Additive manufacturing**: This is a key enabler of agile manufacturing, with applications in the aerospace, automotive, biomedical, and construction industries. For instance, in the aerospace sector, 3D printing has become vital for producing lightweight components using precision engineering (Davim 2019). (See **Exhibits 21, 22, 23** and **24** for AM market data, trade information on AM machinery and investment budgets.)
- **Biomedical sector**: AM is driving innovation **in organ printing and dental implants, as well as in 3D tissue engineering** (Davim 2019). (See **Exhibit 25** for medical technology market data.)

10.6 Geographic addressable market

The adoption of agile manufacturing varies significantly by region in Europe, with countries such as France, Germany, Italy, Poland, Ukraine and Switzerland showing high potential for adoption due to their innovation capabilities, strong industrial bases, and government support for technological advancements.

- **France:** A significant player in European manufacturing, France's industry revenue was $1214 billion in 2018. The sector's value added is projected to reach €254.2 billion in 2024, with a 29% value-added margin. Manufacturing output is expected to be €870.8 billion in 2024, employing 4.81% of the workforce. Key outputs include consumer goods, material products, and industrial products and services (Statista 2024).
- **Germany**: A leader in machinery manufacturing, Germany has extensive manufacturing infrastructure and government initiatives such as cloud computing advancements to support agile manufacturing (United Nations Industrial Development Organization 2023).
- **Italy**: Government initiatives such as the **Piano Transizione 4.0** plan, which provides significant tax incentives for advanced technology, position Italy as an important market (MarketLine 2024).
- **Poland**: Poland's increasing infrastructure projects and trade relationships with neighboring countries, such as Ukraine and Germany, position it as a strong market for agile technologies (Trading Economics 2024).
- **Switzerland**: Known for its high-tech industries, including aerospace and electric machinery, Switzerland offers strong potential for agile manufacturing adoption (MarketLine 2024). (See **Exhibit 26** on regional innovation).
- **Ukraine**: Ukraine's raw materials, skilled labor, and urgent need for resource optimization post-reconstruction make it a promising candidate for agile manufacturing adoption (Cirella 2024).

10.7 Manufacturing sectors for agile manufacturing

- Several key sectors are poised to adopt agile manufacturing, particularly in medium-high and high-technology industries, including electrical equipment, machinery and equipment, and computer and electronic products. These sectors contribute the highest added value globally (UNIDO 2023). (See **Exhibits 11, 15** to **17**, and **25** for additional data on sector-specific markets and materials used in these markets.
- **Aerospace and defense**: AM is transforming production processes in the aerospace sector, particularly in the creation of spare parts and in weight reduction for aircraft (Davim 2019).

10.8 Insights from focus groups on agile manufacturing adoption

After conducting focus groups with various customer types involved in an evolved agile manufacturing business model, several key insights emerged regarding the factors influencing adoption decisions. These insights offer a practical perspective on the benefits and challenges of agile manufacturing technologies from the standpoints of manufacturers, contract manufacturers, and OEMs.

The focus group analysis revealed the following key factors:

- **Cost and time savings**: Agile manufacturing technologies such as laser beam cutting and 3D printing were highlighted as offering substantial cost savings and faster production times, particularly for project-based and seasonal demand. Businesses that operated on a pay-per-use model experienced increased productivity and flexibility, particularly in industries with fluctuating demand.
- **Space and scalability**: One of the challenges identified by smaller manufacturers is the space requirement for some agile technologies. While agile manufacturing enables production flexibility and the ability to scale, limited space can be a barrier for small facilities.

- **Suitability for demand volatility**: The pay-per-use model was found to be economically beneficial, especially for companies with high or consistent monthly demands. However, for facilities with minimal and stable demand, the economic benefits were more limited due to the monthly credit system associated with agile manufacturing technologies.
- **Operational flexibility**: Companies that adopted agile manufacturing in service-oriented models noted that the increased operational flexibility allowed them to respond to external changes faster, leveraging local supplier networks and advanced technologies to enhance cost-effectiveness.

Summary of the advantages and disadvantages: (See **Exhibit 27** for a synthesis of these insights.)

AGM technology adoption demonstrated several advantages:

- **Enhanced productivity**, through flexible production technologies, such as laser cutting and AM.
- **Reduced time to market** and **cost efficiency**, due to the modular and adaptable nature of agile manufacturing systems.
- **Improved scalability**, particularly in industries with dynamic production requirements.

However, certain disadvantages were also noted:

- Space limitations and high initial setup costs could pose challenges for smaller facilities.
- Economic benefits were limited for businesses with low or stable demand, for which the monthly credit system did not provide as much cost savings.

These insights, coupled with quantitative data from manufacturers across industries, highlight how agile manufacturing can drive value, particularly in sectors with variable production cycles and demand fluctuations.

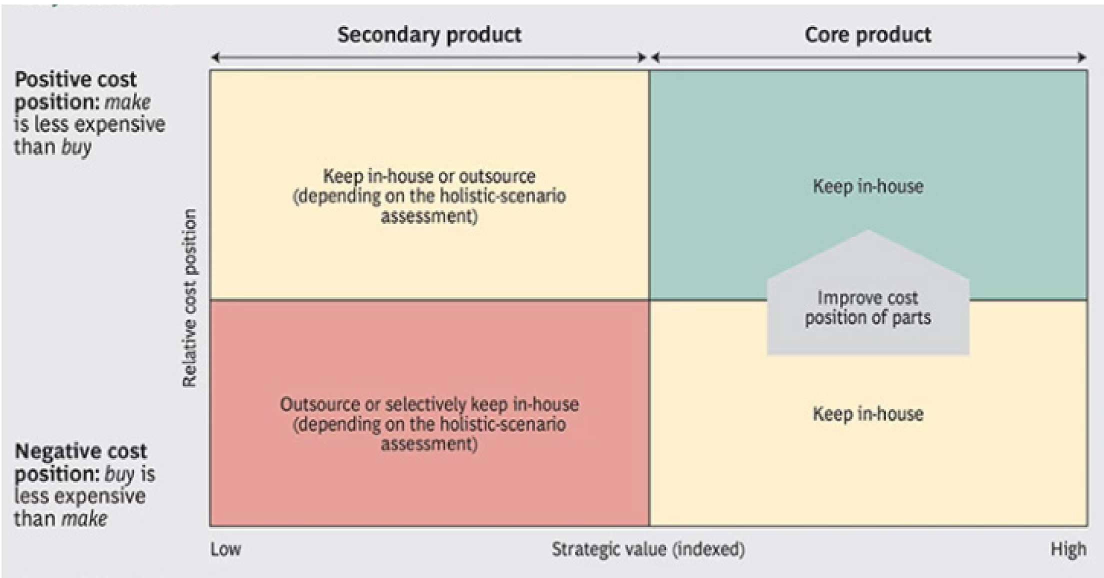
Finally, see **Exhibit 28** for the expected addressable value in Europe and **Exhibit 29** for the addressable market of machine material and parts suppliers in Europe. The aligned visual representations per segmentation are seen in **Exhibits 30** and **31**.

Overall, agile manufacturing adoption is emerging as a crucial paradigm for European manufacturers by offering customized and high-quality products with shorter life cycles. Agile manufacturing requires the integration of Industry 4.0 technologies, which have been observed to transform manufacturing processes and enable innovative business model creation. This access for smaller firms creates opportunities to access advanced manufacturing capabilities and to build competitiveness across the European landscape. Manufacturing sectors, such as the aerospace, and defense sectors, and manufacturing equipment providers will greatly benefit from this adoption. Regions such as France, Germany, Italy, Poland, Spain, Switzerland, and Ukraine will play a great role in this adoption. Ultimately, agile manufacturing ensures resilience and competitiveness in an environment inclusive of ongoing market transformations.

Exhibits

Exhibit 1

Assessments of strategic value and relative cost position are the basis for make-or-buy scenarios



Source: Küpper et al. (2015).

Exhibit 2

Visualizing the factors influencing the adoption or nonadoption of an agile manufacturing business model

Note: The decision-making model of make or buy as a client is based on two options. The "make" represents the option of the manufacturer buying its own machine, and therefore not adopting the agile manufacturing business model. The "buy" represents the decision to adopt the agile manufacturing business model. The chart above is measured on a scale of 0 to 35 in terms of the accuracy of the statements. A score of 35 is very accurate, while a score of 0 is very inaccurate. In the chart, the location of the designated color (red and green) and closeness to the top level of 35 visually represent the decision-making model for the manufacturers.

Adoption of AGM Business Model

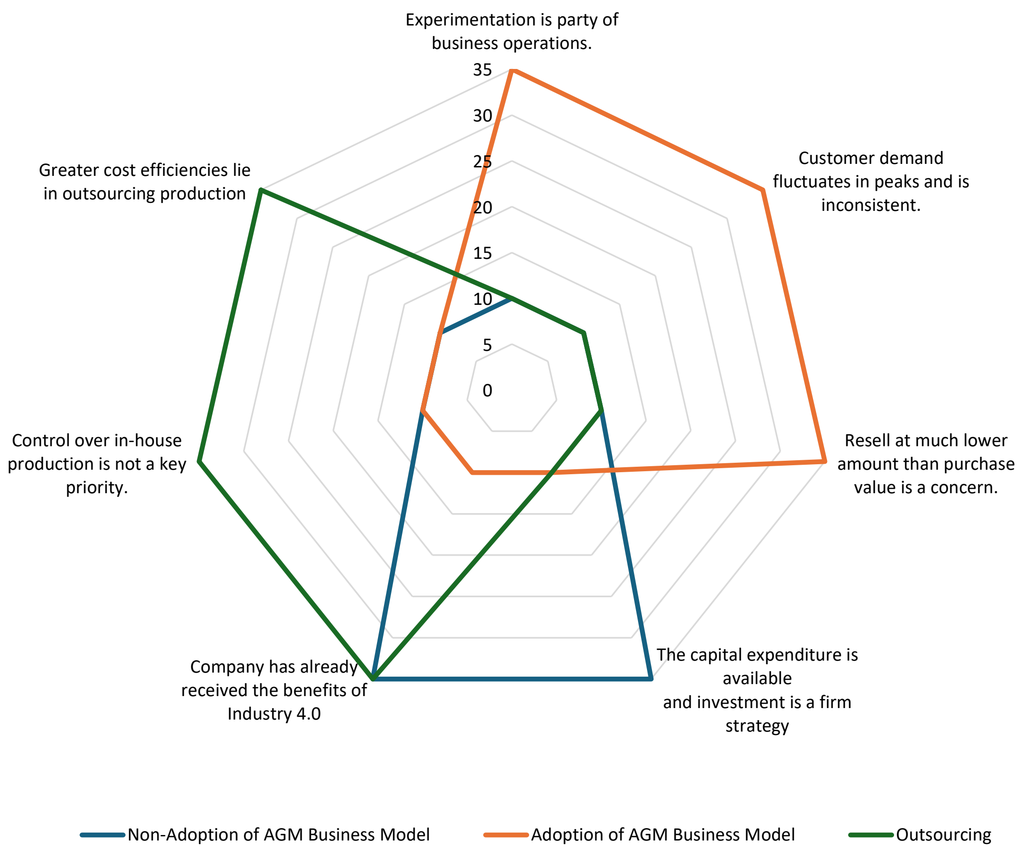


Exhibit 2 (continued)

Dimension	Traditional Manufacturing: Non-Adoption	Adoption of Agile Manufacturing	Outsourcing
Capital expenditure	Capital expenditure is available, while investment is a firm strategy	The capital expenditure is not available, while investment is a not firm strategy	The capital expenditure is not available, while investment is a not firm strategy
Resell value	Reselling at a much lower amount than the purchase value is *not* a concern	Reselling at a much lower amount than purchase value is a concern	Reselling at a much lower amount than purchase value is a concern
In-house control	Control over in-house is a key priority	Control over in-house is a key priority	Control over in-house is not a key priority
Customer Demand	Customer demand is consistent and stable.	Customer demand is inconsistent, seasonal, project-based and/or fluctuates.	Customer demand is consistent and stable.
Industry 4.0	The company has already received the benefits of Industry 4.0	The company has not already received the benefits of Industry 4.0	The company has already received the benefits of Industry 4
Cost efficiencies	It is not more cost efficient to outsource.	It is not more cost efficient to outsource.	It is more cost efficient to outsource.
Experimentation	Experimentation is not a priority to the company.	Experimentation is a priority to the company.	Experimentation is not a priority to the company.

Source: Prepared by the authors.

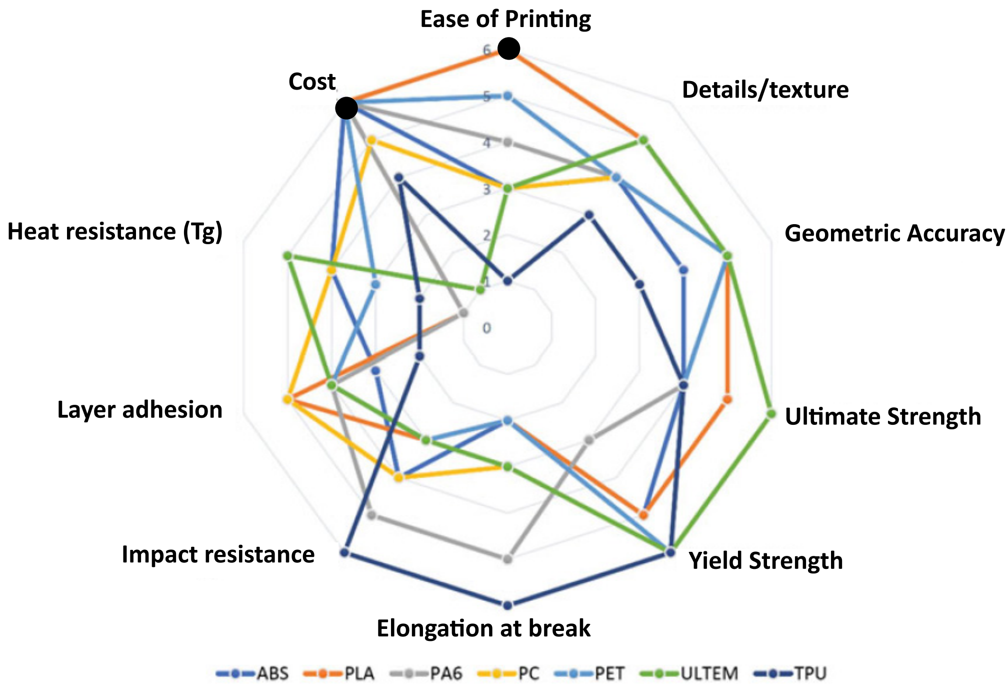
Exhibit 3
Traditional vs. agile manufacturing

Traditional manufacturing	Agile manufacturing
Continuous improvement of internal processes	Proactively responding to external uncertainty with great flexibility
Mass production of standardized products	Individual, customized products
Primary focus on resource efficiency and low-cost production	Stresses excellence in competitive forces outside of cost and quality
Does what has historically worked well	Dynamic, growth-oriented, and adaptable
Reactive; not as adaptable	Due to market instability and product complexity

Source: Prepared by the authors.

Exhibit 4

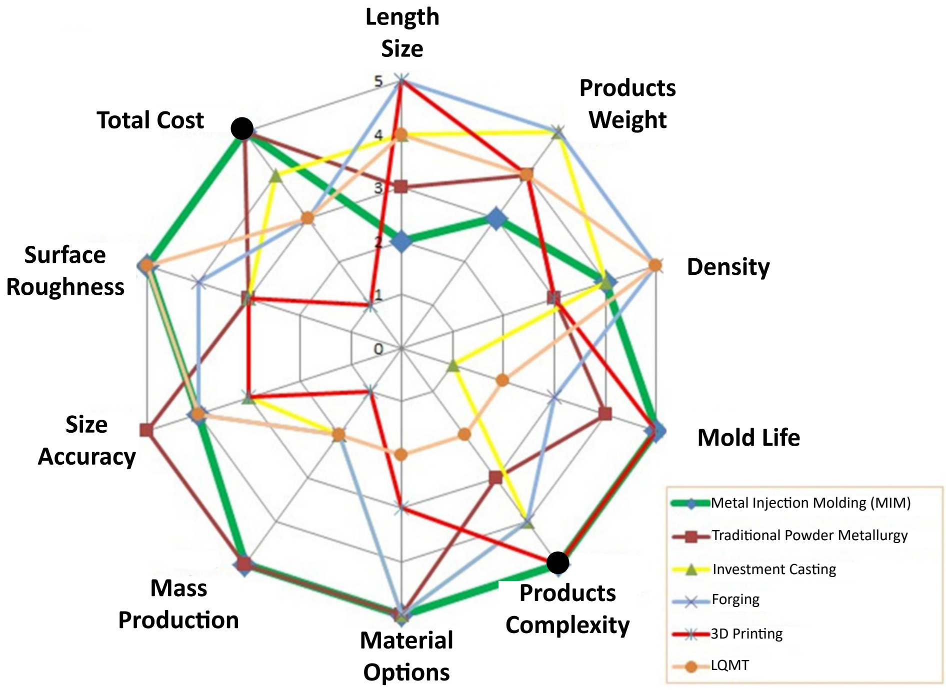
Detailed ranking of factors affecting fused deposition molding



Source: Dave and Patel (2021).

Exhibit 5

Comparative analysis of metal injection molding



Source: Shin Zu Shing Co. Ltd. (2016).

Exhibit 6

Adoptable agile manufacturing technologies and scorecard of adoptability

Manufacturing Technology	Dimensions representing strength	Additive Manufacturing	Laser Beam	Moulding	Welding
Production levels	Fast build speed	1	1	1	1
Material usage	Efficiency, minimal wastage	1	1	1	1
Equipment size	Moderately sized, able to fit in a variety of physical infras-tructure	0.5	0.5	0.5	0.5
Traditional Equipment cost	Low capital expenditure requi-red is optimal	1	1	0.5	0.5
Labor cost	Affordable, low labor cost re-quirements is optimal	0.5	0	0.5	0.5
Ability to incorporate cloud manufacturing	Highly-automated,	1	1	1	1
Flexibility and ability to create complex parts	Great flexibility and adaptability capabilities are optimal	1	1	0.5	0.5
Labor type required	Preferable that the technology does not require complex and highly skilled labor	0	0	0.5	0.5
Batch sizes	Preferable that batch sizes are small, and or individually made	1	1	0.5	0.5
Industry usage	Greater variety of industries, the better	1	1	1	1
Maturity level of adoption	Early adopter is preferred	1	1	1	1
Regulation factors	Preferably, minimal regulation required is present	0	0	0	0
Results of adoptability	Sum of points above	9	8.5	8	8

Manufacturing Type	Die-casting	Thermomechanical Processing	Subtractive manufacturing	Photolithography
Results	7	6.5	8	7

Scorecard	Low strength	Medium strength	High strength
	0	0.5	1

Source: Prepared by the authors and inspired by interviews with industry professionals.

Exhibit 7

Components influencing agile manufacturing technological adoption

Core points	Explanation	Subdimensions
Versatility	Not a Highly Specifically Designed machine created for one process	Technology can produce an expansive variety of parts Technology can conduct a variety of processes
Cost effectiveness	Materials, including consumables are affordable	The materials and consumables included are affordable, and or do not require extensive levels of materials
Transportability	Reasonable size and simple to assemble/disassemble	The machine can be transported, installed, and deinstalled, the size is moderate as well
Used in a widespread industry with high demand	Growing Demand and Customer Base Ex. Automotive in Germany	Used in an industry with continuous growth, high customer demand and a strong customer bas
Is mature or has the capability to be mature	Has been technologically advanced or researched, or is expected to be	Manufacturers are continuously adopting this technology, and greater levels of research are being devoted to the technological advancement
Creates flexible demand	Can meet evolving customer expectations	Can create a variety of products on demand, with shorter production cycles

Source: Prepared by the authors.

Exhibit 8

Trade values of plastics and thereof

Total global trade value and market share (2022)	Germany trade ranking: exporter value (2022)
$864 million, 3.65% market share	Top third, at $86.5 billion

Source: Prepared by the authors based on data from the Observatory of Economic Complexity (2022).

Exhibit 9
Trade values of metals

Total global trade value and market share (2022)	Germany trade ranking: exporter value (2022)
$1.75 trillion, 7.37% market share	No. 2, at $131 billion

Source: Prepared by the authors based on data from the Observatory of Economic Complexity (2022).

Exhibit 10
Trade values for machine parts required for agile manufacturing

Total global trade value and market share (2022)	Germany trade ranking: exporter value (2022)	Trend of machine parts required in agile manufacturing (2021–2022)
$11.1 billion	No. 1, at $2.2 billion	7.23% increase in global trade value

Source: Prepared by the authors based on data from the Observatory of Economic Complexity (2022).

Exhibit 11

Value of European industrial companies and sector specific data

Cash flow of operations value (All european industrial companies)	Market capitalization	Total capital expenditures	Debt capital returns for long-term debt	Debt capital returns for short-term debt	ROI capital 2023	Total non-current assets
€50,136.12 million between the top peers	€751,357.55 million	€13,619.91 million	€3,516.72 million	€1,410.69 million	11.66%	€338,237.4 million

Total assets	Sales value	Sales growth of the top european industrial companies in construction equipment industry	Sales growth of the top european industrial companies in process and discrete automation industry
€647,612.3 million	€0.459 million	5%	12.0%

Aspect details
Primary focus: Alternative fuel vehicles, passenger cars, and motor vehicles
Relevant regions: Germany, Spain, and Europe (excluding China, United States, and Japan)

Source: Prepared by the authors based on the data from Bloomberg Intelligence (2023) and Factiva (2024).

Exhibit 11 (continued)

Wholesale distribution industry capital investment	Raw materials capital investment	Construction and engineering capital investment and companies located in europe	Robotic process automation spending (2022)	Industrial robots installed worldwide in the metal and machinery sector (2022)	Industrial internet of things as a computing technology connection: expected adoption within the next 3 years
€223,01 billion	€258,26 billion	€1.10 trillion, 155,787 companies	$3.7 billion	66,000	65.4%

Aspect details
Gross investment in intangible goods (2020): €258,378.80
Business expenditure on R&D (2020): €127,583.54
Enterprises using cloud computing services (2023): 45.0%
Enterprises analyzing big data internally (2020): 8.8%
Consumer price growth rate of industrial products (2024–2027): 1.2%
Share of Industrial Products in consumption expenditure: 365.51% out of 1,000

Source: Prepared by the authors based on the data from Bloomberg Intelligence (2023) and Factiva (2024).

Exhibit 12
Manufacturing enterprises in Europe

Manufacturing enterprises in Europe	German manufacturing companies
2.89 million manufacturing enterprises	Market Value Added (2022)
Definition: the manufacturing market includes the physical or chemical transformation of materials, substances, or components into new products.	4.8% share value, fourth largest globally

Source: Prepared by the authors based on the data from data provided by Statista (2023) and UNIDO (2023).

Exhibit 13
Markets, products, and sectors. European machinery market, products, and sectors

Total revenue (100 companies)	Machinery as a percentage of world trade	Export value of german machinery, mechanical appliances, and parts industry	Export value of italian machinery mechanical appliances, and parts industry
$5,525.09 billion	10.8%	$251 billion	$105 billion

Source: Prepared by the authors based on the data from by MarketLine (2018) and OECD (2022).

Exhibit 14
Amount per source for European industrial's 2023, and expected values of 2025

Expected amount per source of European industrial's 2025	Amount per source for European industrial's 2023
€17.2 billion in dividends	€16.4 billion in dividends
€13.3 billion CapEx	€13.0 billion CapEx

Source: Prepared by the authors based on the data from Bloomberg Intelligence (2023).

Exhibit 15
3D printing materials market

2018 value of materials market	3d gases market revenue (2020)	CAGR* of 3D printing materials market
$1.53 billion	$43.06 million	**11.97 % CAGR**

*Compound Annual Growth Rate

Source: Prepared by the authors based on data from Statista (2024b).

Exhibit 16
Size of the rubber and plastics market

Total value added (2024)	Germany added value (2024)
$1.53 billion	$38 million

Source: Prepared by the authors based on data from MarketLine (2024).

Exhibit 17
Construction industry

Aspect details
Technology: Additive manufacturing used for customizable parts with minimal material
Additive manufacturing technologies: Binder jetting, extrusion process, powder bed fusion), directed energy deposition

Source: Prepared by the authors based on data from Kumar, Zindani, and Davim (2019).

Exhibit 18

Outsourced technology manufacturing services market

Total annual revenue of eight companies	Total revenue: 1y average growth rate	Total enterprise value/total average revenue
€3690.01 million	0.2547%	3.48x

Source: Prepared by the authors based on the data from S&P Capital IQ.

Exhibit 19

Size of the pharmaceutical contract manufacturing services sector

Total annual revenue of company	Total market capitalization	Total enterprise value/total average revenue
€546.56 million	€1932.71 million	. 2.6475x

Source: Prepared by the authors based on the data from S&P Capital IQ.

Exhibit 20

Hardware market and IT hardware market

Total value of the european hardware market (2023)	Forecast value of the european hardware market (2027)	Market value of the german IT hardware market	Market value of the spanish hardware market	Market value of the italian IT hardware market	Market value personal computer market (2023)	Market value of the consumer electronics retail market (2022)
$102 billion	$120.3 billion	19%	6%	8.5%	$22,615 million	$302.7 billion

Source: Prepared by the authors based on the data from MarketLine (2023) and Statista (2024).

Exhibit 21
AM and EU hardware market continued

Market value (2020)	AM applications (2019, %)	European distribution of AM (2019)	Market value of spanish it hardware market (2022)	Market value of swiss it hardware market (2022)	Total global value of european market	Hardware distribution budget in north america and europe
$12.6 billion	42% (Spain and Italy), 63% (Germany), 74% (France and Belgium), 67% (Switzerland and Austria)	55%,	$4 billion	$1 billion	31%	21% laptops, 16% desktops, 13% servers

Source: Prepared by the authors based on data provided MarketLine 2023. Statista 2024.

Exhibit 22
Data on 3D printing companies

Total value of global 3d printing companies (n = 2584)	Manufacturing value of global 3d printing companies	Advanced manufacturing vertical	3D printing companies in Europe (n = 84)	Ratio of european advanced manufacturing companies to global companies	Top 5 associated sectors of 3D printing
€66.37 billion	€32.45 billion	Capital investment of €18.32 billion (see **Figure 15**)	Median post-valuation of €10.65 million	1,461/5,858	Advanced manufacturing, manufacturing, artificial intelligence, internet of things, and robotics/ drones

Source: Prepared by the authors based on data provided by Pitchbook (2024).

Exhibit 23

Trade values of AM machinery

World trade value (2022)	Value of top exporter (2022)	Value of am machine importers
$12.1 billion	Germany, at $2.31 billion (0.051% of global trade)	Germany, at $1.05 billion; France, $446 million

Source: Prepared by the authors based on data provided by OECD (2022).

Exhibit 24

Manufacturing segment data

Electrical equipment industry capital investment	Aerospace and defense industry capital investment	Machinery industry capital investment	Capital investment for all other industries	Robotics and drones capital breakdown	Infrastructure capital investment and companies located in Europe
€1.02 trillion	€1.30 trillion	€696.66 billion	€16.18 trillion	€228.52 billion	€958.91 billion, 24,515 companies

Source: Prepared by the authors based on data provided by Pitchbook (2024), Statista (2023), Eurostat (2024).

Exhibit 25

European medical technology market

Expected value of the european medical technology market (2023)	Five biggest markets	European medical device market
Approximately €160 billion	France, Germany, Italy, Spain, and the United Kingdom	26.1% of the global market

Source: Prepared by the authors based on data provided by MedTech Europe (2024).

Exhibit 26
Regional innovation levels

Addressable market leaders	European medical device market
Czech Republic	Moderate innovator
Poland	Emerging innovator
Ukraine	
Switzerland	Innovation leader
Germany	Strong innovator
Spain	Moderate innovator
France	Strong innovator
Italy	Moderate innovator

Source: Prepared by the authors based on data provided by the European Commission (2023)

Exhibit 27
Focus group insight synthesis

Benefits of AGM	Disadvantages of AGM	Key Insights
Cost savings through pay-per-use model	Monthly credit system may be costly for low-demand users	Best suited for businesses with consistent or high monthly demand
Time savings from mature AGM technologies	Space limitations can restrict machinery options	Enables flexibility in production
Increased productivity	May not lead to new production capabilities	Particularly beneficial for project-based or seasonal work
Only pay for machines when in use	Potential for unused credits during low-demand periods	Reduces costs associated with idle machinery
Easy to learn software and training	May not be economical for small facilities with stable, minimal demand	Allows quick adaptation to changing customer needs
Enables production agility		Effectiveness depends on business size and demand patterns
Straightforward implementation		Local supplier networks can support AGM adoption
Reduced labor and maintenance costs		Advanced technologies, such as laser cutting, enhance efficiency

Source: Prepared by the authors based on communication with focus group participants.

Exhibit 28

Expected addressable market value in Europe

Financial or numerical values	Description of contributing factor	Source
€ 160,000,000,000.00	Medical technology market in Europe	**Exhibit 25**
€ 953,484,000.00	AM machinery import value to Germany	**Exhibit 29**
€ 405,003,680.00	AM machinery import value to France	**Exhibit 29**
3,906,000,000	AM market value in Europe (31% of 12.6 billion €)	**Exhibit 21**
€ 1,100,000,000,000.00	Engineering capital investment in Europe	**Exhibit 11**
€ 751,357,550,000.00	European industrial market capitalization	**Exhibit 11**
€2,016,622,037,680.00	Total addressable market of adoption in Europe	
Note: The above values have been converted to euros using the current foreign currency rate on 9.17.2024		
1,890,060 companies	Expected number of manufacturing enterprises in Europe as part of the addressable market (Current Enterprises multiplied by expected adoption rate)	**Exhibit 12, Exhibit 21**

Source: Prepared by the authors based on data provided by the sources in the right column.

Exhibit 29

Addressable market of machine materials and parts suppliers in Europe: Focus on Germany

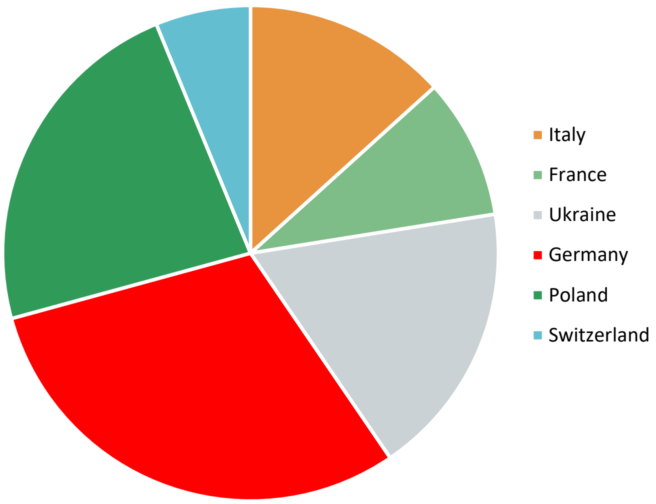
Financial or numerical values	Description of contributing factor	Source
$ 37,800,000,000.00	Rubber and plastics market, Germany	**Exhibit 16**
$ 2,200,000,000.00	Machine parts export value, Germany	**Exhibit 10**
$ 131,000,000,000.00	Metals export value, Germany	**Exhibit 9**
$ 171,000,000,000.00	Addressable market of machine materials and parts suppliers in Europe: Focus on Germany	

Source: Prepared by the authors based on data provided by the sources in the right column.

Exhibit 30

Economies and consumers annual data

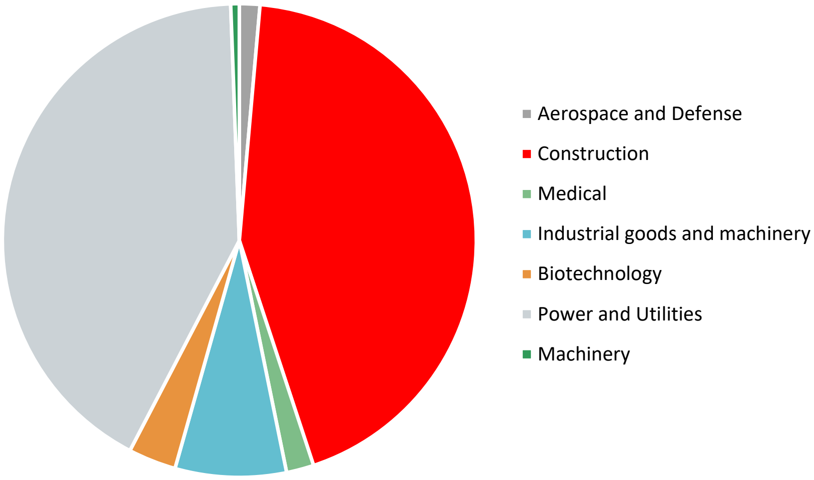
a) Expected segmentation of TAM by geographical location/ measured by Global Value Added Passport Euromonitor



Source: Euromonitor International (2024).

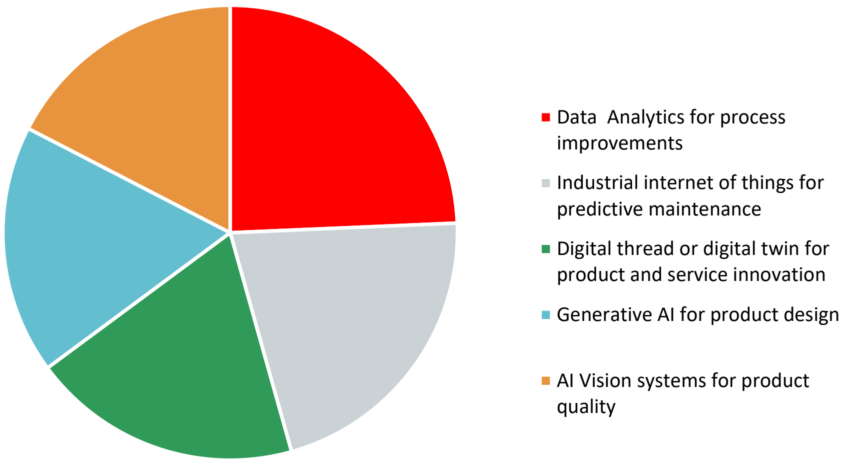
Exhibit 30 (continued)

b) Expected segmentation of TAM by industry



Source:MarketLine (2021).

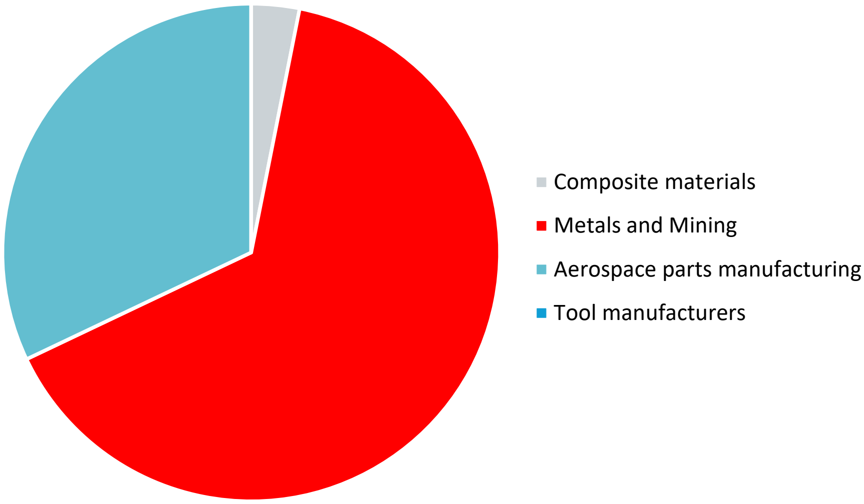
c) TAM segmentation per manufacturing technology, importance of technology use cases in manufacturing organizations, per what consumers deem as very important



Source: Shikanai (2024).

Exhibit 30 (continued)

d) TAM Segmentation by materials, parts and tools manufacturers



Source: MarketLine (2021).

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