ST-674-E
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Agile manufacturing and the pay-per-use model

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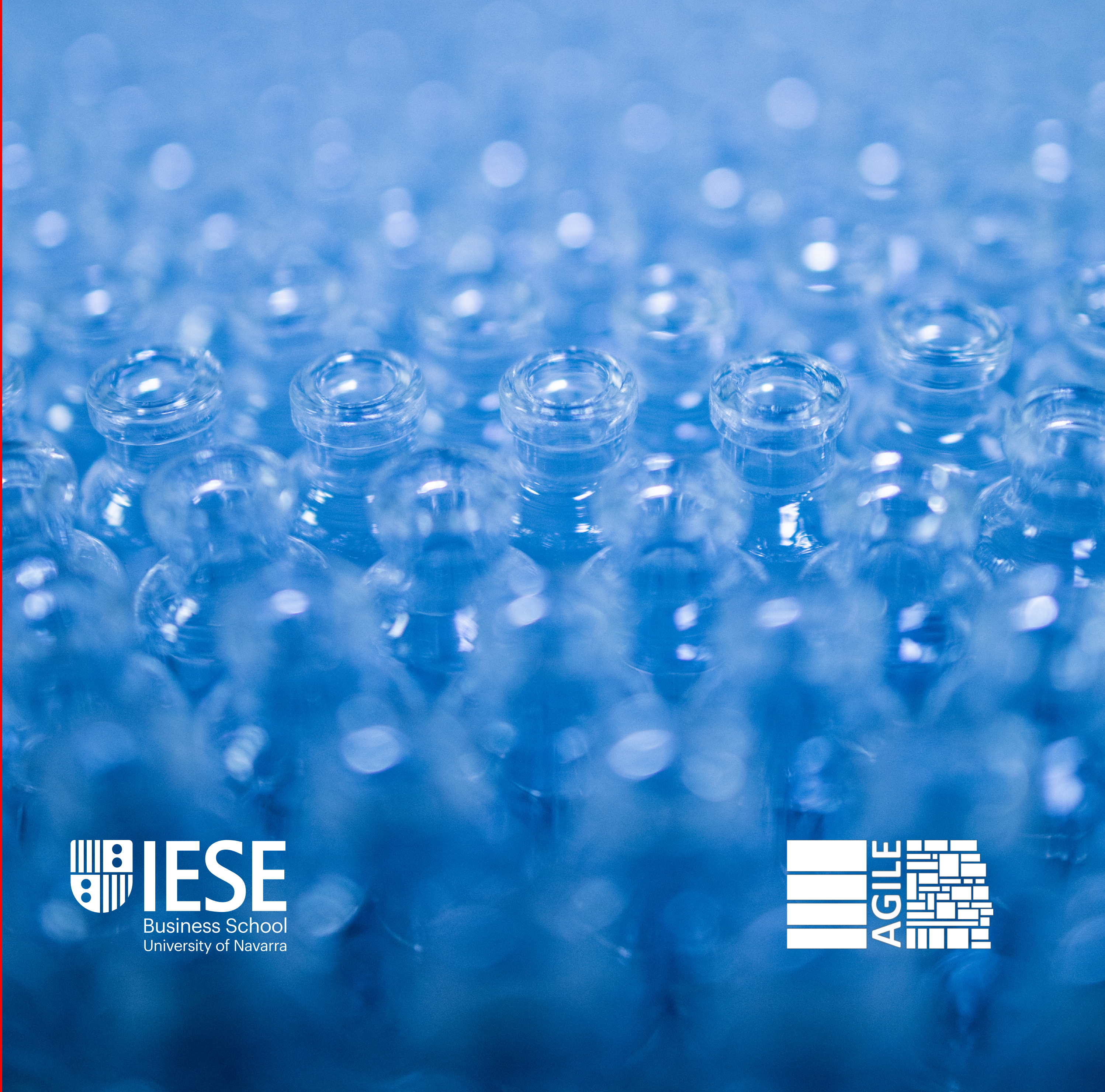

IESE Business School University of Navarra

AGILE

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Artificial Intelligence was used as assistance in the creation of this report in respect to data privacy and ethical research practices. Everything has been reviewed by humans.

All of the material contained in this document has been developed by the authors unless otherwise stated.

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Executive summary: Agile manufacturing and the pay-per-use model

The manufacturing industry is undergoing a profound transformation due to the convergence of Industry 4.0 technologies, supply chain disruptions, and sustainability imperatives. Traditional make or buy strategies are proving inadequate for addressing the demands of customization, agility, and resilience. A third strategic option, agile manufacturing, is increasingly viable and offers operational flexibility through pay-per-use (PPU) models. This model emphasizes access over ownership and responsiveness over volume, enabling manufacturers to reduce capital risk, scale dynamically, and innovate continuously.

Agile manufacturing leverages Industry 4.0 technologies, such as artificial intelligence (AI), the Internet of Things (IoT), and additive manufacturing, to create flexible and digitally enabled production systems. The PPU framework minimizes fixed costs and bases pricing on actual machine usage while bundling services like maintenance, training, and analytics to ensure operational reliability. This strategic approach aligns with global shifts toward innovation-centric, resilient, and sustainable industrial ecosystems.

Key findings and adoption trends

1. **Firm profiles:**
    - **Agile innovators—**Typically 4 to 10 years old with high R&D intensity and global reach, these firms are early adopters and ideal candidates for pilot deployments.
    - **Cautious mid-sizers—**Regional firms with moderate R&D budgets and hybrid production models; while open to agile manufacturing, they require reassurance on ROI and operational integration.
    - **Traditionalists—**Older firms reliant on manual and subtractive methods; these entities are resistant to change, prioritizing cost containment and predictability over innovation.

2. **Adoption predictors:** Firms with high R&D investments (above 5% of revenue), strong innovation priorities, mid-sized revenues, and operational maturity (ages 4 to 10 years) are most likely to adopt PPU frameworks. Early adopters are predominantly innovation-driven firms that use advanced technologies like additive manufacturing.

3. **Barriers to adoption:** Common obstacles include misconceptions about infrastructure requirements, concerns over control and transparency, and unclear ROI. Many firms fall into indecision due to a lack of education, financial unclarity, and perceived operational risks.

4. **Adoption curve:** Adoption follows a classic S-curve, with early traction between 2025 and 2028, scaling between 2029 and 2035. Ten to fifteen percent of manufacturers are structurally aligned for early PPU adoption.

5. **Geographic and sector insights:**
    - Europe emphasizes sustainability goals but faces fragmented industrial policies.
    - The United States benefits from centralized policies like the CHIPS Act (Creating Helpful Incentives to Produce Semiconductors and Science Act) and the Inflation Reduction Act to support digital infrastructure.
    - Advanced Asian economies show readiness for agile technologies but may prioritize internal innovation over externalized models.

Strategic recommendations

1. **For technology providers:**
   - Shift from product-centric sales to strategic partnerships. Tailor solutions by segment, focusing on education, ROI tools, and pilot programs.
   - Reframe relationships as long-term partnerships, bundling services like training, analytics, and product innovation into seamless offerings.

2. **For manufacturers:**
   - Begin with targeted pilot programs in noncritical production lines to test agile manufacturing models and build internal confidence.
   - Transition financially from capital expenditures to operating expenditures by adopting budgeting and forecasting methodologies suited for PPU models.

3. **For policy-makers:**
   - Offer tax incentives, subsidies, and innovation adoption vouchers to de-risk PPU adoption for small and mid-size firms.
   - Invest in public–private training programs and smart infrastructure to enable broader participation in agile manufacturing ecosystems.

Conclusion

Agile manufacturing through PPU models represents a transformative pathway for the global manufacturing industry. By enabling firms to scale capacity dynamically, experiment with emerging technologies, and reduce capital risk, this strategy fosters resilience and competitiveness in an evolving industrial economy. However, its widespread adoption relies on overcoming misconceptions, aligning incentives, and fostering collaboration among technology providers, manufacturers, and policy-makers. Agile manufacturing is not just an operational shift but a strategic enabler for the next era of industrial innovation.

1. Introduction: The rise of agile manufacturing

Over the past decade, global manufacturing has entered a period of profound transformation driven by three converging macro forces: the rise of Industry 4.0, persistent supply chain shocks, and growing imperatives around sustainability and resilience. In this new landscape, traditional operating models—whether vertically integrated or outsourced—are proving increasingly inadequate at meeting the demands of accelerated product life cycles, customization, and geopolitical uncertainty.

Industry 4.0 technologies such as artificial intelligence (AI), the Internet of Things (IoT), robotics, and additive manufacturing have created the infrastructure for a more responsive, data-driven production systems. At the same time, the COVID-19 pandemic, semiconductor shortages, and geopolitical tensions have exposed the fragility of globalized supply chains, forcing firms to reconsider cost-optimized strategies in favor of agility and resilience. Meanwhile, sustainability expectations from customers, regulators, and investors are pushing manufacturers to reduce capital intensity, optimize asset use, and minimize environmental impact.

In response to these pressures, a third strategic option has emerged alongside the traditional make or buy choices: make it agile.

First introduced in our earlier work (Jané and Hill 2024, hereafter ST-660-E), the make–buy–agile framework posits that firms are no longer confined to choosing between in-house ownership and external outsourcing. Instead, they can adopt a hybrid path—leveraging shared, flexible, and digitally enabled production systems such as agile manufacturing supported by pay-per-use (PPU) models. These models emphasize access over ownership, responsiveness over volume, and service integration over fixed assets (ST-0660-E).

While the theoretical underpinnings of agile manufacturing are well-developed, a critical gap remains: how ready are real-world manufacturing firms to adopt these new models? Until now, the literature has largely focused on conceptual frameworks, with little empirical insight into organizational readiness, adoption timelines, and perceived barriers.

This study addresses this gap by integrating the theoretical architecture of agile manufacturing with new empirical data from 45 manufacturing firms across Europe and North America. Through this synthesis, we aim to provide a robust and actionable perspective on where agile manufacturing stands today—and how it can be accelerated for tomorrow.

2. Theoretical foundations and framework

The theoretical basis for agile manufacturing lies in the convergence of two major trends: the strategic imperative for flexibility and the technological capacity for responsiveness. Drawing from ST-0660-E, we define agile manufacturing as a capability-driven model that enables firms to rapidly adjust their operations in response to market changes, product variation, and demand volatility—without sacrificing cost efficiency or quality. The theoretical foundations developed in ST-0660-E were based on both the qualitative analysis of current theories and interviews with industry professionals.

Key drivers of agility

Agility in manufacturing is driven by a triad of forces:

- **Responsiveness:** The ability to react quickly to market fluctuations and supply chain disruptions.
- **Customization:** The capacity to deliver personalized or short-run production without major retooling or delays.
- **Innovation:** The structural openness to experiment, iterate, and deploy new technologies, processes, or business models.

Role of enabling technologies

Agile manufacturing is powered by the integration of Industry 4.0 technologies, which create a digital and physical backbone for flexibility:

- **AI:** Enables predictive maintenance, dynamic scheduling, and real-time optimization.
- **IoT:** Facilitates machine-to-machine communication and live production monitoring.
- **Big data analytics:** Informs product development, quality control, and supply chain coordination.
- **Additive manufacturing:** Supports rapid prototyping and decentralized, low-volume production.

These technologies are not merely tools but enablers of strategic agility, allowing firms to decouple volume from efficiency and asset ownership from capability.

The "make it agile" paradigm

Traditional production strategy forces firms into a binary choice:

- **Make:** High control and customization but capital-intensive and rigid
- **Buy:** Asset-light and flexible but with limited control and integration

Agile manufacturing introduces a third path:

- **Make it agile:** Firms retain strategic control over production while accessing capabilities through servitized models (e.g., PPU and platform-as-a-service). This allows experimentation, fast scaling, and strategic alignment without heavy capital investment.

Agile manufacturing maturity model

In our original framework, we proposed a maturity model that assesses firms based on the following:

- Operational agility (flexible scheduling and changeover speed)
- Digital maturity (integration of AI/IoT/data platforms)
- Strategic alignment (innovation culture and responsiveness)
- Business model flexibility (readiness for servitized or shared asset models)

The Agile Manufacturing Maturity Radar provides a benchmarking framework that helps organizations assess their current state of agility and identify targeted pathways for transformation. This model compares the ideal state of full agile readiness with actual readiness reported by respondents in survey ST-673-E.

The analysis is based on weighted responses to key questions, each mapped to a core dimension of agility:

- **Operational agility:** "Do you consider your organization to be agile?"
- **Digital maturity:** "Which manufacturing technologies do you use?"
- **Strategic alignment:** "How important are innovation and experimentation to your business?"
- **Business model flexibility:** "How likely are you to adopt this model?"

Each response was translated into a scale from 1 to 5, and the weighted average for each dimension is visualized in the radar chart below. This offers a holistic view of how closely current capabilities align with agile manufacturing ideals.

Please see **Figure 1** for an analysis on the agile manufacturing maturity radar.

Figure 1. Agile Manufacturing maturity radar

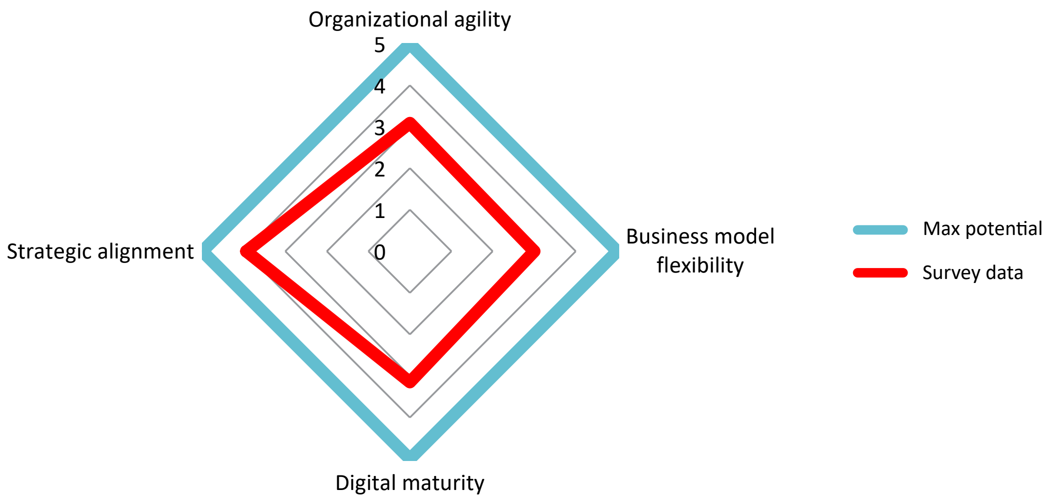


Figure 1 illustrates a moderate level of agile readiness across all four dimensions. Respondents demonstrated strength in strategic alignment (score: 3.94), indicating that innovation and experimentation are seen as important strategic priorities within their organizations.

However, the remaining dimensions—digital maturity (3.15), organizational agility (3.09), and business model flexibility (3.00)—suggest that while the mindset may be in place, the operational and structural enablers for agility are still maturing.

- **Digital maturity:** Adoption of enabling technologies like automation and additive manufacturing is underway but not yet widespread.

- **Organizational agility:** Many respondents see themselves as only somewhat agile, reflecting room for improvement in cross-functional responsiveness and adaptability.

- **Business model flexibility:** A conservative stance toward adopting new models (e.g., PPU) signals structural or cultural barriers to agile experimentation.

The organizations surveyed are strategically aligned with agile principles but must focus on operational execution and digital enablement to realize their full agile potential.

The following table provides descriptions of the five levels analyzed in this model.

Table 1. Analysis of agile manufacturing maturity model

Level	Operational agility	Digital maturity	Strategic alignment	Business model flexibility
1. Initial/ad hoc	Uncoordinated, reactive, low flexibility	Manual processes, rigid scheduling, slow changeovers	Minimal tech use, siloed data, no IoT or AI	Fixed, product-centric business model
2. Managed/defined	Some structure and planning, limited responsiveness	Basic scheduling tools, some changeover planning	Basic digital tools (e.g., ERP), minimal data use	Awareness of alternative models but no implementation
3. Integrated/ repeatable	Standardized processes, emerging agility	Efficient changeovers, adaptive scheduling based on data	IoT-enabled monitoring, some predictive analytics	Some services or asset-sharing models tested
4. Agile/proactive	Cross-functional agility and responsiveness	Real-time reconfiguration, dynamic resource allocation	Integrated AI/IoT platforms, advanced analytics	Servitization and shared models operational in parts
5. Optimized/ transformative	Fully agile, self-optimizing operations	Autonomous scheduling, instant changeovers	End-to-end digital twin, AI-driven decisions	Highly adaptive, platform-based, service-oriented model

Make–buy–agile decision tree

The original paper introduced a decision tree framework guiding firms through a series of strategic questions:

1. Is customization a key differentiator?
2. Are volumes predictable or variable?
3. Does the firm have digital infrastructure in place?
4. Is rapid experimentation or prototyping critical?
5. Are capital constraints limiting traditional investment?

Firms that answer "yes" to these questions are more likely to benefit from agile manufacturing pathways.

3. Research design and methodology

To complement and test the theoretical propositions developed in *Agile manufacturing,* ST-660-E, an empirical study was conducted and published under the name of *Quantitative analysis of agile manufacturing* 2025 (Jané and Hill 2025, hereafter ST-673-E). The goal was to explore how real-world manufacturers perceive and potentially adopt agile manufacturing, particularly when enabled by a PPU business model. While the theory outlined strong drivers and clear frameworks, practical validation was necessary to assess market readiness and adoption dynamics.

Survey population and sample composition

The empirical study was based on survey data collected from 45 manufacturing firms operating in Europe and North America. The sample was intentionally diverse to capture a broad cross-section of the manufacturing landscape. Participating firms varied according to the following characteristics:

- **Sectors:** Aerospace, automotive, biomedical, electronics, industrial equipment, construction, energy, and Fast Moving Consumer Goods (FMCG).
- **Company type:** OEMs, Tier 1 and Tier 2 suppliers, startups, and hybrid entities.
- **Geography:** 11 countries across Western, Central, and Eastern Europe, with additional responses from the United States.
- **Technology use:** Respondents self-reported on their usage of traditional, subtractive, automated, and additive manufacturing technologies.

This diversity allowed for segmentation analysis based on organizational type, technological maturity, and geographic reach.

Definition of the PPU model

To ensure consistency and relevance in interpretation, the survey introduced participants to the concept of agile manufacturing through a PPU business model. This model was defined as a production system characterized by minimal fixed costs and variable pricing based on actual machine usage. The core technology was a versatile, digitally enabled machine offering smart capabilities (e.g., IoT, predictive maintenance, and remote support), deployed on-site with integrated services such as maintenance, training, and upgrades. Respondents were explicitly asked to evaluate their likelihood of adopting such a model under this definition.

Research hypotheses

The study tested two main hypotheses:

1 **Hypothesis One:**
Firms' manufacturing decisions—to make (in-house), buy (outsource), or make it agile (adopt agile manufacturing)—are influenced by:

- Manufacturing segment (in-house, hybrid, or outsourced)
- R&D investment level
- Innovation and experimentation priority
- Annual revenue
- Company age

2 **Hypothesis Two:**
The total addressable market (TAM) for agile manufacturing can be estimated using the following equation:

TAM = Global manufacturing market
× (%) using additive, subtractive, or automated technologies
× (%) of firms less than 10 years old
× (%) with moderate to high innovation priority
× (%) investing >5% of annual revenue in R&D
× (%) with domestic or global customer base

This formula offers a firm-level framework for identifying agile manufacturing adoption potential based on strategic, financial, and operational criteria.

Methodology

The study employed a mixed-methods quantitative approach:

- **Logistic regression—**Used to assess binary outcomes such as the likelihood of adopting the PPU model (likely vs. unlikely) based on categorical predictors like sector or company classification.

- **Ordinary least squares (OLS) regression—**Used to test continuous outcome variables, such as likelihood scores or revenue-based segmentation.

- **Multinomial and visual analysis—**Adoption likelihood was also analyzed across more granular scales (e.g., five-point adoption likelihood) using bar charts, stacked distributions, and predicted probability curves to visualize trends across technology types, organizational age, and innovation posture.

This methodology enabled a robust and nuanced analysis of adoption readiness and highlighted the variables most strongly associated with openness to agile manufacturing.

4. Key findings: Who is adopting agile manufacturing?

The empirical findings from ST-673-E provide important insights into the types of firms most receptive to agile manufacturing via PPU models. While adoption remains in the early stages, the data reveals clear patterns in organizational readiness, structural constraints, and attitudinal barriers.

4.1 Organizational predictors of adoption

Adoption intent is most strongly associated with specific internal characteristics, suggesting that agile manufacturing appeals to firms with both innovation ambition and operational maturity. The most consistent predictors of adoption were the following:

- **Innovation priority—**83% of respondents ranked innovation and experimentation as “moderately,” “very,” or “extremely” important strategic goals (ST-673-E). These firms were significantly more likely to indicate openness to PPU adoption. Companies that were open to more innovative manufacturing technologies (automated and additive) were slightly more likely to adopt the PPU model in comparison to more moderate (subtractive) and conservative (traditional users) users.

- **R&D intensity—**Firms that invest more than 5% of their annual revenue into R&D showed the highest levels of adoption readiness. Among these, “extremely likely” adoption rates were concentrated to the 10–25% R&D investment bracket.

- **Company age—**The segment of companies aged 4–10 years emerged as the most enthusiastic adopters. These firms are generally mature enough to have stable operations and resources but young enough to embrace experimentation and change.

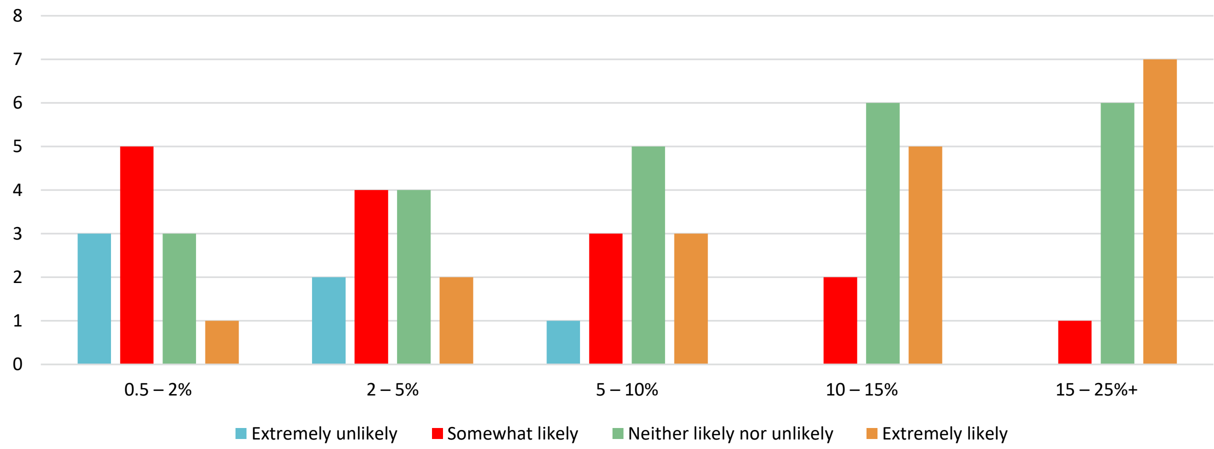
- **Revenue size—**Adoption likelihood rose in parallel with revenue size, particularly in the $50M–$200M range. Smaller companies (< $2M revenue) showed greater reluctance, citing financial and infrastructural constraints.

- **Openness to new manufacturing technologies—**Responses were categorized as conservative, moderate, and open regarding manufacturing technology openness. Firms in the open category were more likely to adopt the PPU model.

These findings suggest that mid-sized, innovation-oriented firms represent the early adopters of agile manufacturing. They have both the motivation and capability to embrace servitized production models without being constrained by legacy infrastructure or organizational inertia.

See the **Figures 2** to **5** through five for visualizations of the distribution of R&D budget and adoptability, innovation priority and adoptability, company age and adoptability, as well as manufacturing technology openness and adoptability.

Figure 2. Distribution of adoption likelihood by R&D budget



4.2 Structural factors and weak predictors

Surprisingly, some structural variables assumed to be important proved statistically insignificant (ST-673-E):

- **Manufacturing sector—**Logistic regression revealed no meaningful correlation between industry type (e.g., pharma, automotive, and electronics) and likelihood of PPU adoption. While electronics and digital firms showed directional openness, small sample sizes limited statistical significance.

- **Company classification—**Whether a firm was a startup, OEM, or Tier 1 or Tier 2 supplier had no predictive value for adoption intent.

- **Manufacturing model (in-house, hybrid, and outsourced)—**Manufacturing segmentation did not significantly affect adoption likelihood, though hybrid manufacturers displayed the highest baseline openness to PPU.

While these factors did not statistically predict adoption, qualitative insights suggest that hybrid firms—those combining internal production with selective outsourcing—may be more strategically flexible and operationally suited for a modular model like PPU.

4.3 Barriers to adoption

Despite a generally high level of interest in agile manufacturing, several adoption barriers emerged that help explain the current implementation gap (see **Figure 3**):

- **Perceived infrastructure constraints—**The most frequently cited reason for non-adoption was "lack of physical infrastructure," followed closely by "lack of technological infrastructure." These responses reflect a common misconception: that PPU requires capital-intensive, ownership-based investments—when in fact, it is designed to minimize them.

- **Fear of losing control—**Especially among firms with negative outsourcing experiences, concerns about transparency, service quality, and operational control were prevalent. These fears exist despite the PPU model offering improved monitoring, service level agreements (SLAs), and on-site presence.

- **Neutral attitudes and unclear ROI—**A substantial proportion of respondents fell into the "neither likely nor unlikely" category, indicating indecision rather than rejection. These firms may require stronger evidence of ROI, fit with existing systems, or competitive benchmarking to overcome inertia.

Together, these findings underscore that while the theoretical value of agile manufacturing is well understood, practical adoption hinges on de-risking perceptions, educating on infrastructure realities, and aligning messaging with firm-specific constraints.

Figure 3. Distribution of adoption likelihood by innovation priority

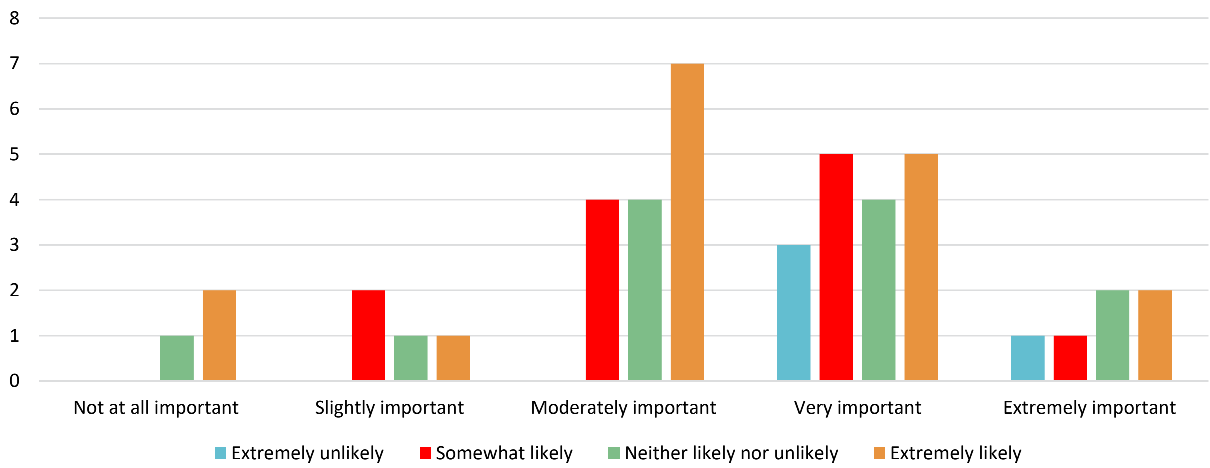


Figure 4. Distribution of adoption likelihood by company age

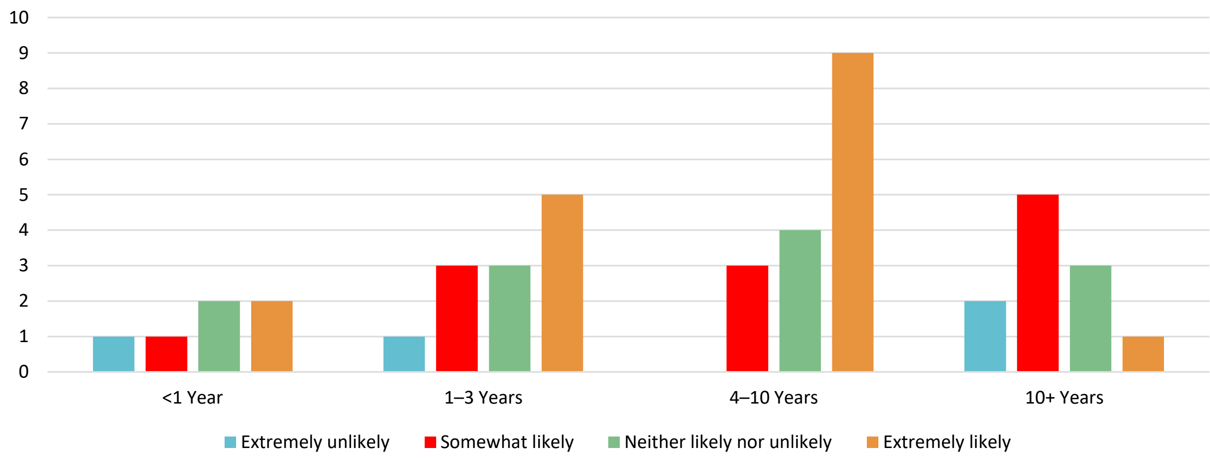
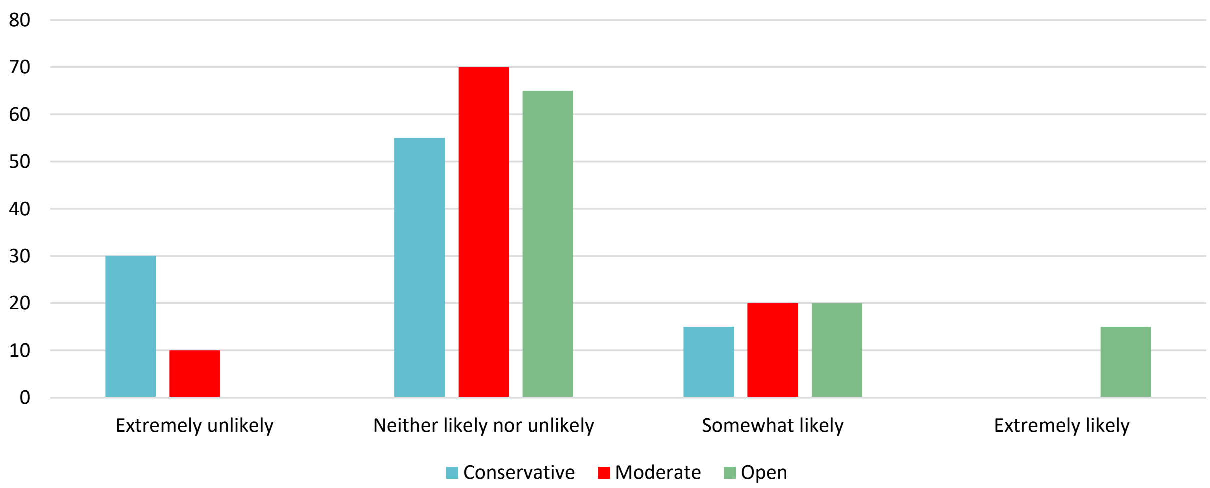
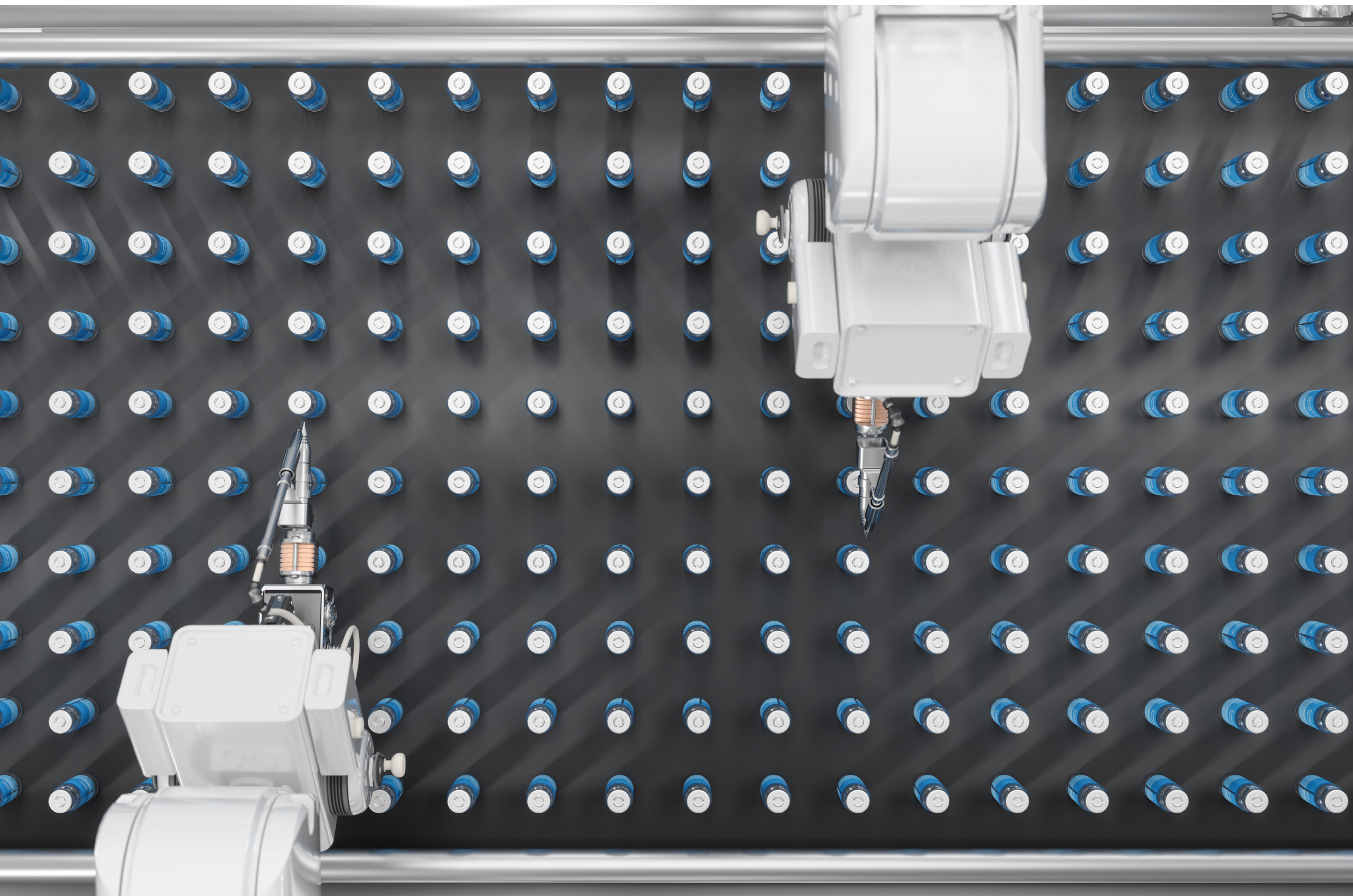


Figure 5. Impact of technology openness on likelihood of adoption





5. From resistance to readiness: Industry profiles

To help manufacturers, technology vendors, and policy-makers navigate the evolving Agile Manufacturing landscape, this section synthesizes real-world adoption patterns into three actionable firm archetypes. These profiles map closely to the theoretical personas introduced in **ST-660-E**, offering a bridge between conceptual models and empirical evidence.

5.1 The agile innovator

Profile summary

These firms are highly receptive to PPU adoption and exemplify the core tenets of agile manufacturing. They are innovation-driven, strategically global, and technologically advanced.

Key traits

- R&D intensity: > 10% of annual revenue invested in R&D
- Innovation priority: Rated as “extremely important”
- Technology stack: Heavy use of additive manufacturing, cloud computing, and AI-enabled systems
- Market reach: Global customer base
- Firm age: Typically 4–10 years, signaling both operational maturity and innovation hunger

Adoption behavior

- Show highest levels of “extremely likely” PPU adoption
- View agile manufacturing as a natural extension of servitization strategies
- Often early adopters or candidates for pilot deployments

Strategic opportunity

These firms represent the tip of the spear for driving adoption. Vendors should engage them as launch partners and case study collaborators to validate and showcase the model’s benefits.

5.2 The cautious mid-sizer

Profile summary

These firms are interested but hesitant, balancing traditional practices with moderate innovation goals. They see the potential of agile manufacturing but require reassurance and proof of fit.

Key traits

- R&D Intensity: 2–5% of revenue
- Innovation priority: “Very” or “moderately important”
- Technology stack: Hybrid usage of traditional and subtractive methods (e.g., CNC and injection molding)
- Manufacturing model: Hybrid (some in-house, some outsourced)
- Market reach: Primarily regional (e.g., within the EU or North America)
- Revenue: $50M–$200M
- Firm age: Typically mid-stage (4–10 years)

Adoption behavior

- Fall predominantly into the “somewhat likely” and “neither likely nor unlikely” categories
- Main concerns include ROI visibility, operational disruption, and infrastructure clarity
- Often lack internal champions for radical change

Strategic opportunity

This group represents the early majority. They require targeted education, financial modeling tools, and risk-mitigated pilot programs. Trust-building is key—particularly around ROI, integration ease, and service quality.

5.3 The traditionalist

Profile summary

These firms exhibit low interest or active resistance against agile manufacturing. Their operations are built around predictability, control, and cost containment.

Key traits

- R&D Intensity: < 2% of revenue
- Innovation priority: “Slightly” or “not at all important”
- Technology stack: Reliant on traditional manufacturing (e.g., manual assembly, welding, and casting)
- Market reach: Local or single-country focus
- Firm age: Often > 10 years, with legacy systems and entrenched processes
- Manufacturing model: In-house or fully outsourced

Adoption behavior

- Overrepresented in the “extremely unlikely” category
- Commonly have misconceptions about infrastructure costs and technology requirements
- Concerned with compliance burdens, internal capability gaps, and potential loss of control

Strategic opportunity

These firms are not immediate targets for adoption. However, over time, they may be swayed through proof-of-concept success stories, simplified onboarding pathways, or regulation-induced disruption (e.g., compliance with Environmental Social Governance (ESG) mandates or traceability standards).

By understanding where firms fall along this readiness spectrum, suppliers and ecosystem partners can better align messaging, tools, and incentives. Agile manufacturing is not a one-size-fits-all solution—it must be contextualized to each firm's strategic posture, operational model, and innovation appetite.

Table 2. Firm archetypes in agile manufacturing adoption

Variable	Agile innovator	Cautious mid-sizer	Traditionalist
Firm age	4–10 years	4–10 years	> 10 years
R&D intensity	> 10% of annual revenue	2–5% of annual revenue	< 2% of annual revenue
Innovation priority	Extremely important	Moderately to very important	Slightly or not important
Technology stack	Additive, AI, IoT, cloud native	Hybrid: subtractive + some automation	Traditional: manual, subtractive methods
Market reach	Global	Regional (EU, North America)	Local or single-country
Adoption readiness	Extremely likely to adopt agile manufacturing	Somewhat likely/ uncertain	Extremely unlikely
Manufacturing model	Flexible, servitized, often pilot-ready	Hybrid (in-house + outsourced)	Rigid, in-house, or fully outsourced
Strategic outlook	Innovation-led agility	ROI-focused caution	Control and cost containment

6. Recommendations for industry

Agile manufacturing, enabled by PPU business models, offers transformational potential—but its successful adoption hinges on tailored strategies. This section presents actionable guidance for both technology providers and manufacturing firms, grounded in the research findings from ST-0660-E (theoretical) and ST-673-E (empirical).

6.1 For technology providers: Enablers of scalable adoption

Technology vendors, equipment manufacturers, and integrators must move beyond product-centric sales to become strategic adoption partners. The research identified key levers for accelerating adoption based on firm profiles and decision-making behaviors.

a. Segment-based go-to-market strategies

A one-size-fits-all approach is ineffective. Providers should tailor messaging and solutions based on firm archetypes:

- Agile innovators (high R&D, additive-first firms)—Offer these firms pilot co-creation, advanced analytics, and ecosystem partnerships. Position them as flag bearers and early case studies.

- Cautious mid-sizers—Emphasize to these firms modular deployment, ROI guarantees, and easy onboarding. De-risk their experimentation with financial transparency and hybrid service models.

- Traditionalists—Lead with education and benchmarking. Position PPU as a tool to gradually modernize infrastructure without major CapEx exposure.

b. Tools to overcome common objections

Adoption barriers often stem from misperceptions, not reality. To address these, focus on the following:

- Training and education—Offer onboarding modules, factory floor simulations, and staff enablement to demystify usage.

- Free or subsidized pilot programs—Leverage these especially for mid-tier firms hesitant to commit without proven benefits.

- ROI calculators and business case templates—Help buyers visualize the switch from fixed costs to variable cost models (operating expenses (OpEx)).

- SLAs—Address control and quality concerns raised by outsourcing-experienced firms.

c. Reframe the relationship: From vendor to strategic partner

Firms are not just buying equipment—they are betting on an agile operating model. Vendors must do the following:

- Provide multi-year roadmaps, not transactional sales
- Bundle services (maintenance, analytics, and training) into a seamless experience
- Demonstrate reliability, uptime, and innovation co-development capability

By doing so, they transition from solution sellers to long-term capability enablers.

6.2 For manufacturing firms: Building an agile future

Manufacturers face pressure to become more responsive, resilient, and digitally enabled. For firms exploring agile manufacturing and PPU, the research offers a stepwise path to de-risked adoption.

a. When to consider agile manufacturing

Firms should consider agile manufacturing if they experience any of the following:

- Volatile or seasonal demand (e.g., food, packaging, and apparel)
- Rising outsourcing pain (quality, supply risk, and lack of flexibility)
- Need for innovation (e.g., prototyping and rapid iteration)
- Compliance burden (e.g., regulated sectors like pharma or aerospace)
- Desire to reduce CapEx exposure while expanding capacity

Agile manufacturing is not only a growth strategy—it is a risk management strategy.

b. Start small: Test before you scale

Rather than transforming end-to-end systems immediately, firms can consider the following:

- Deploy a pilot line with a PPU partner in a noncritical product line.
- Introduce additive manufacturing nodes for design iteration, customization, or spare parts.
- Use agile approaches in new product development (NPD) cycles to test integration, speed, and cost.

Success in one cell or business unit builds internal momentum and confidence for broader rollout.

c. Plan financially for a CapEx-to-OpEx shift

The most fundamental changes that occur with the implementation of PPU models are financial:

- Budget planning must shift from large upfront capital expenditures (CapEx) to recurring OpEx.
- Finance teams must adjust forecasting models, depreciation assumptions, and performance metrics.
- Firms may also need to engage external financial partners for usage-based leasing, insurance, or service guarantees.

This shift supports financial agility, allowing firms to scale manufacturing spend in line with actual demand and strategic cycles.

By aligning capabilities with strategic intent and leveraging segmented guidance, both providers and manufacturers can move from interest to execution—accelerating the transition toward an agile industrial economy.

7. Refined TAM model

One of the central goals of this study was to estimate the TAM for agile manufacturing enabled by PPU models. While Hypothesis 2 in **ST-673-E** did not yield statistically significant predictors in regression models, the descriptive data enabled a refined TAM framework grounded in observable behavioral patterns.

7.1 Updated TAM formulas

We also considered Hypothesis two which posited a formula for estimating the TAM for agile manufacturing based on key organizational characteristics. Although the original hypothesis was not **statistically supported**, refinements suggest that adoption potential correlates with a narrow subset of firm-level traits.

An updated model used to estimate the global Total Addressable Market of agile manufacturing is proposed as follows:

$16.177 trillion: global manufacturing ouput as of 2023 (MacroTrends, 2023)
× 0.45 (% of firms investing more than 5% of their annual budget in R&D)
× 0.83 (% that prioritize innovation and experimentation at a moderate to high level)
× 0.899 (% of firms less than 10 years old)
× 0.808 (% operating in mid-to-high revenue tiers)
× 0.629 (% using automated, subtractive, or additive manufacturing technologies)

Estimated TAM: $2.48 trillion

It's important to note that the characteristics used to refine the TAM estimate—such as R&D intensity, innovation focus, firm age, revenue tier, and technology use—are based on insights from a small, targeted empirical study rather than broad industry datasets. These attributes reflect patterns specific to the surveyed sample and may not fully capture the diversity of the broader manufacturing landscape. As such, while they offer useful directional insight into which firms may be more receptive to new business models, the findings should be interpreted with caution. The segmentation criteria are best understood as illustrative filters shaped by a limited dataset—not definitive indicators of industry-wide behavior.

7.2 Implications for regional competitiveness

The adoption of agile manufacturing will vary not only by firm type but also by region, based on industrial ecosystems, innovation incentives, and infrastructure:

- Europe shows stronger alignment with sustainability-linked agility goals but more fragmentation in tech infrastructure and industrial policy.
- The United States benefits from bold, centralized policy (e.g., CHIPS Act and IRA), and a robust venture ecosystem for hardware and services (National Institute of Standards and Technology, n.d.; U.S. Congress, n.d.)
- Asia features advanced regions (e.g., Japan, South Korea, and Singapore) that are tech-ready but may prioritize internal innovation pipelines over externalized PPU models.

Regions that align public policy, infrastructure investment, and Small Medium Enterprise (SME) enablement will gain competitive advantage in the global manufacturing shift.

8. Implications for policy-makers

Policymakers play a pivotal role in shaping the pace and inclusiveness of agile manufacturing adoption. Governments that see manufacturing as a strategic asset must move from passive regulators to proactive ecosystem builders.

8.1 Incentivize agile transformation

Governments can help reduce risk and improve ROI for adopting firms through the following:

- Tax credits for usage-based manufacturing technologies (similar to R&D tax relief)
- CapEx–to–OpEx subsidies that support initial PPU contracts or infrastructure retrofits
- Innovation adoption vouchers for SMEs seeking to pilot agile technologies

Examples include the U.S. Inflation Reduction Act and CHIPS Act, both of which include embedded manufacturing provisions tied to clean energy, semiconductors, and digital industrial infrastructure.

8.2 Build agile manufacturing capacity

Agile models require a digitally fluent workforce, smart infrastructure, and collaborative ecosystems. Policymakers should proceed as outlined below:

- Expand public–private training programs for digital operators, robotics technicians, and smart factory managers.

- Co-invest in regional innovation hubs focused on agile production (e.g., Germany's Fraunhofer Institutes or Manufacturing USA in the U.S.) (Fraunhofer Society, n.d.; Manufacturing USA, n.d.).

- Facilitate cross-border collaboration to harmonize standards, especially in the EU, where fragmentation hinders agile scale-up.

Public policy must act as a bridge-builder, ensuring that the benefits of agile manufacturing extend beyond tech leaders to traditional industries and SMEs.

9. Future research

While this integrated study provides a strong conceptual and empirical foundation, many research questions remain unanswered. Future work should explore the areas discussed below.

9.1 Longitudinal adoption studies

PPU adoption is not a static event but a multi-year transition. Longitudinal studies could assess the following:

- Track early adopters across 2–5 years.
- Identify organizational learning curves, success metrics, and barriers to scale.
- Measure economic and operational outcomes (e.g., cost reductions, agility gains, and product development speed).

9.2 Real-world implementations

There is a growing need for case-based validation, including the following:

- Field experiments comparing traditional and PPU lines.
- Supply chain integration studies (e.g., how PPU affects lead times or inventory turns).
- Impact of PPU on product quality, innovation velocity, and workforce skill evolution.

These studies could be co-led by academic–industry consortia or public–private testbeds.

9.3 Sector-specific behavioral drivers

Behavioral and strategic priorities vary by industry. Future research could compare the following:

- Pharmaceuticals—High regulation, long cycles; does PPU reduce risk?
- Textiles—Cost-driven, customization-heavy; how to balance PPU economics?
- Machinery—Capital-intensive, durable products; can agility coexist with long asset lives?

9.4 Cultural and leadership dimensions

PPU adoption is not just technological—it is cultural. Further inquiry should explore the following:

- Role of CEO risk orientation in model experimentation
- Influence of national or corporate culture on openness to servitization
- Internal organizational champions and resistance mechanisms

Understanding the human factors of agility will be as critical as the technological ones in shaping the future of manufacturing.

10. Conclusion: A strategic pathway to resilience

The global manufacturing landscape is undergoing a structural transformation. Traditional dichotomies—make or buy—are no longer sufficient to address the demands of a volatile, digitized, and sustainability-driven economy. This study, integrating both theoretical (ST-0660-E) and empirical (ST-673-E) research, confirms the growing viability of a third path: make it agile.

Agile manufacturing, enabled through PPU models, offers firms the ability to scale capacity dynamically, experiment with emerging technologies, and reduce capital risk—all while maintaining control and compliance. It is not merely an alternative pricing model but a strategic enabler of flexibility, resilience, and continuous innovation.

Our findings show that the firms most ready for this shift—those with mid-to-high revenues, strong innovation cultures, and operational maturity—are already signaling intent. Yet widespread adoption will depend on correcting misconceptions, aligning incentives, and lowering barriers to entry.

To accelerate this transformation, stakeholders across the ecosystem must act in coordination:

- Technology providers must reframe their offerings as strategic partnerships, supported by training, transparent value metrics, and flexible onboarding.
- Manufacturers must rethink production as a service opportunity, where agility trumps asset ownership in long-term competitiveness.
- Policymakers must create fertile ground for adoption through targeted incentives, smart infrastructure, and workforce development.
- Researchers and educators must continue to explore, document, and disseminate models of successful transition to agile manufacturing.

In sum, agile manufacturing—anchored in PPU models—is not a fringe innovation. It is a strategic pathway to industrial resilience, economic competitiveness, and national security. The manufacturing renaissance will not be achieved by returning to old models; instead, we must reshape them around the principles of responsiveness, collaboration, and adaptive capacity.

As we move into the next industrial era, the choice is no longer just make or buy—it is how to make it agile.

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