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MAJA SAJDAK
MICHAŁ MŁODY

Influence of Industry 4.0 technologies on strategic agility

Abstract

Research background and purpose: Amidst escalating market volatility, manufacturers are increasingly leveraging Industry 4.0 technologies to enhance strategic agility. However, a nuanced understanding of their influence on core agility dimensions—strategic sensitivity, entrepreneurial dynamism, operational flexibility, and strategic leadership—remains limited. The purpose of the study is to evaluate how Industry 4.0 technologies support various aspects of strategic agility in manufacturing companies.
Design/methodology/approach: The study employs a qualitative methodology, involving in-depth interviews with 11 informants from three selected manufacturing industry sectors. Data analysis was conducted using research triangulation, thereby increasing the credibility.
Findings: The results indicate that Industry 4.0 technologies significantly support the strategic agility of companies, particularly in the areas of strategic sensitivity and strategic entrepreneurship by enabling faster identification and response to market changes and improving collaboration and innovation. Operational flexibility is also strongly enhanced by automation and improved data analytics, allowing companies to adapt more quickly to changing market demands. The impact of technologies on strategic leadership is less noticeable, as it still largely depends on human factors.
Value added and limitations: This study advances understanding of Industry 4.0's impact on strategic agility in manufacturing. The study expands existing theoretical frameworks by integrating concepts co-creating strategic agility, such as dynamic capabilities and the resource-based view, with the Industry 4.0 perspective. Additionally, it highlights the complementary role of human leadership in effectively deploying these technologies, offering a nuanced understanding of the interplay between technological innovation and strategic management. For practitioners, the study offers actionable insights into leveraging Industry 4.0 technologies to boost strategic agility. By understanding these dynamics, companies can optimize production processes, reduce errors, and sustain a competitive edge. Our study's limitations include its focus on Polish manufacturing firms, potential biases from qualitative methods, and a narrow scope of technologies, highlighting the need for broader, quantitative research across industries and Industry 4.0 solutions like blockchain and quantum computing.

Keywords: *Industry 4.0, strategic agility, technologies 4.0, agility attributes*
JEL Classification: L1, L2, L6, M2, O31, O32

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Maja Sajdak ✉
Department of Strategic Management, Poznań University of Economics and Business, Al. Niepodległości 10, 61-875, Poznań, Poland; email: maja.sajdak@ue.poznan.pl
ORCID: 0000-0003-0638-0609

Michał Młody
Department of Strategic Management, Poznań University of Economics and Business, Poland, ORCID: 0000-0001-5368-9719

1. Introduction

The Fourth Industrial Revolution has attracted considerable attention from researchers in recent years, as has the concept of strategic agility, which is a crucial capability for companies in turbulent conditions. Agility is defined in various ways in literature, and its interrelationships with Industry 4.0 technologies are studied from different perspectives. In essence, strategic agility embodies competitive capabilities that empower organizations to adapt swiftly and effectively to fluctuating environments, thereby ensuring sustained competitiveness and responsiveness. Sen (2020) highlights the imperative of re-evaluating traditional management concepts considering Industry 4.0 advancements, noting that rapid technological changes necessitate a renewed focus on agility within change management practices.

Academic literature emphasizes that modern technologies not only support business operationally but also have strategic significance (Ghobakhloo, 2018; Lib et al., 2018). From a strategic perspective, transitioning to Industry 4.0 requires agility, ensuring integration of key functional areas (Sony & Naik, 2020). Götz (2019) highlights organizational agility as vital for responding to environmental changes and reconfiguring business models. Strategic agility enables organizations to act proactively, essential in today's complex business environment (Doz & Kosonen, 2008). Its role in improving performance grows with business dynamism (Ivory & Brook 2018), maximizing strengths and ensuring survival (Doz & Kosonen, 2008; Ping et al., 2018; Tallon et al., 2019). Ping et al. (2018) emphasize strategic agility as essential for navigating turbulent environments.

Some previous research and studies have examined the impact of agility on digital transformation (Rawashdeh et al., 2024; Bresciani et al., 2021; de Oliveira-Dias et al., 2023). Other researchers adopted different perspectives and have assessed the impact of technologies on agility in some specific areas of a company, e.g., supply chain (Raji et al., 2021; Shahzad et al., 2024), information system (Gou et al., 2019) or creating customer value ("customer agility") (Wamba 2022). However, none of the studies comprehensively address strategic agility by identifying which Industry 4.0 technologies support agility and to what extent (Piccarozzi et al., 2018). Thus, our perspective includes the relationship between the use of Industry 4.0 technologies and the development of four agility attributes (Figure 1). We pose the research question: do Industry 4.0 technologies support strategic agility, and if so, to what extent? Given the above, this article aims to assess how leading Industry 4.0 technologies support the four identified agility attributes, thereby comprehensively supporting strategic agility.

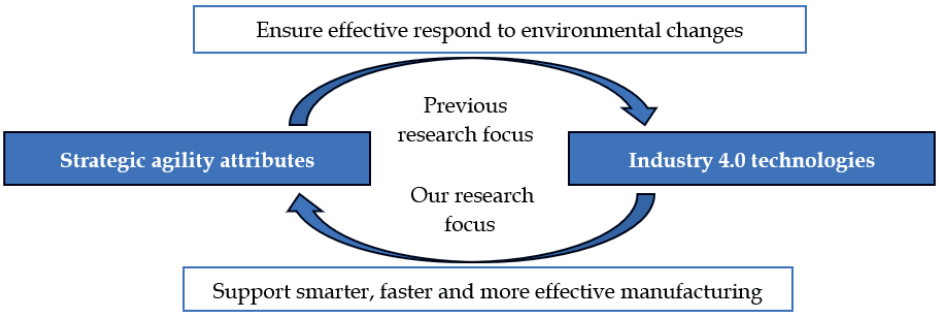

Figure 1. **Two-way relation between strategic agility and Industry 4.0 technologies**

Source: own elaboration

To achieve this aim, the paper presents qualitative research results based on the interview method with key informants (Alvesson & Ashcraft 2012). The interviews were conducted in three industries that widely implemented advanced Industry 4.0 technologies, i.e. food, automotive, and furniture industries (Mehta et al., 2018; Sahoo et al., 2024). Our research results allow for a better understanding of the complex relationships between Industry 4.0 technologies and strategic agility and provide managers with specific guidelines for selecting and implementing Industry 4.0 technologies that can support adaptive capabilities.

The article's structure is as follows: section 2 examines the importance of Industry 4.0 and strategic agility. Section 3 outlines the qualitative research methodology and companies' descriptions. Sections 4 and 5 present main research results and highlight the impact of Industry 4.0 on strategic agility attributes and discuss new theoretical insights on manufacturing management. The conclusion summarizes findings, research limitations, and implications for managers.

2. Bridging Industry 4.0 and strategic agility: synergizing technology and strategic agility attributes

2.1. Industry 4.0: revolutionizing through advanced technologies

Digital transformation has become a key focus for academics and practitioners as businesses struggle to keep pace with technological advancements (Konopik et al., 2022). This paradigm shift has compelled companies to prioritize digital transformation as a key strategic area (Rawashdeh et al., 2024; Gebhardt et al., 2022; Hofmann et al., 2019). As the boundaries between the digital and physical

worlds begin to blur, technological breakthroughs and digital transformation are forcing companies to rethink and reconsider their value-generation strategies. Many consulting companies have attempted to identify technologies with the greatest potential to disrupt the current functioning of the economy and society, so-called disruptive technologies (Nadkarni & Prügl, 2021). Key disruptive technologies include IoT, cloud computing, robotics, 3D printing, and ICT solutions (Henke & Willmott, 2018; Păvăloaia & Necula, 2023). However, the catalog of technologies remains open, and the boundaries between them are sometimes difficult to define in practice. Technologies often emerge as combinations, a process evident in previous industrial revolutions but now accelerated (Arthur, 2009). This mechanism was also visible during previous industrial revolutions but occurred much more slowly due to, for example, the pace of knowledge transfer. The essence of effective digital transformation lies in implementing existing technologies that can be considered mature. While some Industry 4.0 technologies are mature, others remain in development or testing phase. According to Kearney (2020), Industry 4.0 is essentially an ecosystem of five core technologies: 1) artificial intelligence (AI), 2) IoT, 3) 3D printing, 4) advanced robotics, and 5) wearables, augmented reality (AR), and virtual reality (VR). Simultaneously, other Industry 4.0 technologies are also being rapidly adopted, and their market reach has expanded in recent years. Industry 4.0 technologies necessitate the intensive use of large data sets and processes, organized within various subsystems of the organization. The main goals are to improve efficiency, create new opportunities, develop innovation capability (Zhen et al., 2023) and enhance organizational resilience (Shahzad et al., 2024). The transformation of the company forces managers to understand the opportunities, challenges, and emerging competency gaps in the implemented business model (Bharadwaj et al., 2013; Schwab, 2016; Verhoef, 2021). The manufacturing sector plays a key role in adapting Industry 4.0 technologies, which enable increased automation, real-time monitoring of production processes, and optimization of supply chains (Jamwal et al., 2021). As Kagermann et al. (2013) note, "changing technology will also have far-reaching organizational implications, providing an opportunity to develop new business and corporate models and facilitating greater employee engagement." Industry 4.0 enables manufacturers to achieve a new level of operational efficiency and flexibility by integrating advanced technologies such as IoT, robotics, and AI into their production processes. Implementing these technologies requires manufacturing companies not only to invest in new tools but also to develop employee competencies and adapt organizational structures to new requirements (Lasi, 2014). At the same time, the evolution of the technologies themselves and their potential applications complicates the long-term approach to investing in such technologies and planning the entire ecosystem in which the company operates.

2.2. Strategic agility: thriving in a dynamic business environment

Thriving in dynamic environments requires operational flexibility and strategic agility (Holbeche, 2018). According to Mavengere (2013), the survival and growth of businesses significantly depend on their ability to understand and maneuver through the dynamic and increasingly complex business landscape. Companies must develop agility to adapt to evolving competition and business models (Doz, 2020).

Strategic agility enhances performance by enabling rapid, efficient responses to change (Sajdak, 2015; Tallon & Pinsonneault, 2011). According to Doz and Kosonen (2008), strategic agility involves companies making company strategic commitments while remaining flexible enough to adapt to ongoing changes driven by increasing strategic disruptions. Although there is a consensus among scholars that agility involves the ability to perceive and adapt to changes, conceptualizations of agility differ across various organizational levels (such as corporate, business unit, process, or work group) and theoretical frameworks (Tallon et al., 2019). In academic literature, organizational agility and strategic agility are sometimes used interchangeably, emphasizing the importance of agility in quickly recognizing and addressing opportunities and challenges (Tallon & Pinsonneault, 2011; Ravichandran, 2018). We follow the framework of strategic agility proposed by Sajdak (2015) which includes four main attributes: strategic sensitivity, strategic entrepreneurship, operational flexibility, and strategic leadership.

Strategic sensitivity, the first component, involves the ability to assess opportunities and a propensity for risk-taking. This includes quickly identifying market opportunities and threats and determining whether they align favorably or unfavorably with the company's objectives (Zhang & Sharifi, 2000). Sensitivity also involves evaluating emerging opportunities to see if they align with the company's goals and assessing their value independently of the current strategy (Maskell, 2001). The company must also be capable of assessing the risks associated with new opportunities (Sajdak, 2019).

Strategic entrepreneurship enhances adaptability by identifying and exploiting environmental opportunities, fostering strategic flexibility, agility, and innovation (Kraus et al., 2011). It encompasses collaboration, innovation capacity, and entrepreneurial spirit, leveraging innovations through opportunity exploration (Sajdak 2015). Collaboration involves acquiring resources and building networks (Zhang & Sharifi, 2000; Maskell, 2001). Innovation capability is shown in adopting new technologies and resources, with a focus on experimentation and leadership in innovation (Jambulingam et al., 2005; Huang & Li, 2009). Entrepreneurial culture encourages creativity and autonomy through a flat organizational structure.

Operational flexibility, including operational aspects, is the ability to quickly adapt processes and reallocate resources in response to environmental changes (Sajdak 2015). It encompasses flexible production, logistics, marketing, and sales processes (Chan et al., 2017; Yousuf et al., 2019).

The final component, strategic leadership, involves organically emerging leaders. Effective leadership drives change and adaptation (Crocitto, 2003; Crossan et al., 2008). Strategic leadership comprises anticipating, flexibility, strategic thinking, and collaboration (Ireland & Hitt, 2005).

There is a noticeable strong influence of individual theoretical approaches in building the key features that co-create strategic agility (Table 1). By presenting the premises of selected theoretical approaches, their role in shaping the attributes of the theoretical construct of agility is highlighted. Resource Based View (RBV) (Barney, 1991) emphasizes the importance of an organization's unique resources in achieving competitive advantage. RBV enables an understanding of how an organization's unique resources can be leveraged to quickly respond to market changes, which is crucial for agility. Dynamic Capabilities (Teece et al., 1997) stress the organization's ability to continuously identify and exploit new opportunities and reconfigure its resources in response to changing conditions. Strategic agility, at its core, is fundamentally linked to the concept of dynamic capabilities (Nguyen et al., 2024).

Table 1. **Integration of theoretical approaches with attributes of strategic agility**

Agility attribute	Theoretical framework	Relation between theory and agility attribute
Strategic sensitivity	Resource Based View (Barney, 1991)	Identifying and leveraging internal resources to capitalize on opportunities.
	Dynamic Capabilities (Teece et al., 1997)	Sensing, seizing, and reconfiguring resources to adapt to changes.
Strategic entrepreneurship	Theory of Constraints (Goldratt, 1984)	Addressing bottlenecks and leveraging resources to enhance agility.
	Dynamic Capabilities (Teece et al., 1997)	Recognizing opportunities while maintaining adaptability and innovation.
	Relational Capital (Nahapiet & Ghoshal, 1998)	Building relationships and networks to foster collaboration and resource acquisition.
Operational flexibility	Dynamic Capabilities (Teece et al., 1997)	Reconfiguring resources and processes to respond to market changes.
	Theory of Constraints (Goldratt, 1984)	Managing constraints for smoother operations and resource utilization.
Strategic leadership	Transformational Leadership (Bass, 1985)	Inspiring change, fostering innovation, and driving towards a shared vision.
	Relational Capital (Nahapiet & Ghoshal, 1998)	Building strong relationships to enhance collaboration and achieve goals.

Source: own elaboration

Dynamic capabilities involve restructuring competencies to adapt to change (Teece et al., 1997). This framework underpins the theoretical foundation of strategic agility, emphasizing the necessity for organizations to continuously perceive, detect, and capture opportunities through strategic maneuvers and reconfiguration of organizational structures. Theory of Constraints (Goldratt, 1984) focuses on identifying and managing constraints that affect organizational performance. This approach helps understand how organizations can effectively manage their constraints to enhance flexibility and agility. Transformational Leadership (Bass, 1985) highlights the role of inspiring and motivating leadership in transforming organizations and supporting innovation. Transformational leadership fosters innovation and adaptation essential for agility. Relational Capital (Nahapiet & Ghoshal, 1998) emphasizes the importance of building and maintaining strong relationships within and outside the organization. This concept helps understand how relationships and networks can support an organization's innovation and adaptability.

Above mentioned theoretical approaches reinforce the conceptual foundations of strategic agility and offer practical insights for navigating complex, dynamic environments. However, frameworks like RBV and Dynamic Capabilities fall short in addressing the systemic complexity and rapid technological integration characteristic of Industry 4.0, emphasizing the need for their adaptation to meet contemporary demands.

3. Methodology

Our study employed a qualitative research methodology, ideal for exploring new concepts and relationships where existing theories are insufficient (Graebner, 2012). Qualitative research involves extensive engagement with the field to gather data from the perspectives of participants, emphasizing their experiences (Miles & Huberman, 1984). In-depth interviews allowed senior executives to share their experiences with implementing Industry 4.0 technologies, enabling flexibility and the identification of emerging themes. Open-ended questions avoided bias and adapted to participants' responses.

Manufacturing companies in Poland are in the early stages of Industry 4.0, focusing on production automation with limited IT integration (Młody, 2019; Müller et al., 2018; Frank et al., 2019). Adoption lags behind developed economies due to significant barriers (Sokołowski & Markowska, 2021; Jankowska et al., 2023). This study focuses on three key industries of the economy—automotive, food, and furniture. The rationale for selecting these industries is based on both their high degree of digitization, as evidenced in existing literature (Konur et al. 2021; Yasin et al. 2021), and their substantial importance to the Polish economy. The automotive sector is widely regarded as a leader in innovation, particularly in its adoption of Internet of Things (IoT) solutions and advanced data analytics. The food sector, through production automation, contributes

to enhanced food quality and safety (Mehta et al., 2018). Meanwhile, the furniture sector is rapidly integrating digitalization techniques and production lines operated by robots (Sahoo et al., 2024). Interviews conducted in these three industries capture varying levels of Industry 4.0 implementation and enable comparisons with divergent business models. This approach supports a comprehensive assessment of the challenges and benefits associated with digital transformation, while also informing recommendations for further development of innovative industrial solutions. The decision to include 11 companies reflects the need to balance data representativeness with the depth of qualitative inquiry. Methodologically, this sample size allows for a diverse perspective on Industry 4.0 adoption, while preserving sufficient detail in the collected data and avoiding excessive dispersion. Furthermore, recruitment followed the principle of theoretical saturation: the process continued until subsequent interviews no longer yielded new, significant insights. As a result, the empirical foundation is both robust and nuanced, enabling well-grounded conclusions about the characteristics and challenges of digital transformation in the three analysed industries.

We conducted the study between June and August 2023, interviewing senior managers from six large and five medium-sized companies. Key company characteristics, such as establishment year, employment, and profitability, are summarized in Table 2.

Table 2. **Companies' characteristics (data for 2023)**

		Established in:	Main products	Employment
Food industry	Alpha	1993	Dairy products	800
	Beta	2012	Fruit and vegetable juices	350
	Gamma	1990	Diverse assortment of products	n/a
	Delta	1989	Dairy products	960
Furniture industry	Epsilon	2003	Furniture accessories	350
	Zeta	2002	Furniture	100-250*
	Eta	2014	Furniture	100-250*
	Kappa	2006	Furniture	100-250*
Automotive industry	Lambda	2004	Automotive parts	220
	Sigma	2003	Automotive parts	1900
	Omega	2007	Automotive parts	730

* Lack of precise data

Source: own elaboration

Interviews were conducted remotely and totaled 18 hours and 53 minutes, with an average duration of 103 minutes. The longest interview lasted nearly 2 hours, and the shortest 55 minutes, depending on participants' availability. All interviews were recorded, transcribed, and analyzed by two researchers using triangulation. A codebook, initially based on Industry 4.0 technologies and strategic agility attributes, was expanded to include secondary themes. The analysis, summarized in four tables, provided a holistic view of technology-agility relationships.

4. Research results

Managers in manufacturing sector recognize the benefits of Industry 4.0 and its positive effects on strategic agility attributes (de Oliveira-Dias et al., 2023). They also emphasize that specific technologies facilitate the agility of the company as a whole. I4.0 technologies enable faster, data-driven decisions, improving quality and supporting strategic agility (Młody et al., 2023; Wanasida et al., 2021). Our research results are analyzed through four agility attributes: strategic sensitivity, entrepreneurship, operational flexibility, and leadership. Tables summarize the impact of technology on each attribute, with 'NR' indicating insufficient data or lack of implementation.

In the context of **strategic sensitivity** (Table 3), we noted that 3D printing/scanning, advanced data analytics, and Big Data offer the greatest support for agility. These technologies are utilized across all surveyed industries. Managers noted that 3D technologies support opportunity exploitation across industries. In the food sector, they aid prototype visualization, enabling quick customer evaluations (Beta). In furniture, 3D printing accelerates design and texture application (Zeta). Automotive companies use 3D for reverse engineering and component testing, ensuring faster market response (Lambda, Omega).

Table 3. **The impact of technology on strategic sensitivity**

Attributes of strategic agility / Industry 4.0 technologies	**Strategic sensitivity**								
	FOOD INDUSTRY			**FURNITURE INDUSTRY**			**AUTOMOTIVE INDUSTRY**		
COMPANY	Alpha	Beta	Gamma	Zeta	Eta	Kappa	Lambda	Sigma	Omega
3D printing/3D scanning	✓	✓	NR	✓	✓	NR	✓	NR	NR
IoT/M2M	NR	NR	✓	NR	NR	NR	NR	NR	NR
AI	NR	NR	NR	NR	NR	NR	NR	NR	NR

Cloud computing	NR	NR	✓	NR	NR	NR	NR	NR	✓
Smart, mobile devices, smart, mobile apps	NR	NR	NR	NR	NR	NR	NR	NR	NR
Industrial robotics, incl. collaborative robots	NR	NR	NR	NR	NR	NR	NR	NR	NR
Advanced BI solutions	NR	NR	✓	NR	✓	NR	NR	NR	NR
Advanced data analytics / Big Data	NR	NR	✓	NR	✓	NR	NR	✓	✓
Blockchain technology	NR	NR	NR	NR	NR	NR	NR	NR	NR
VR/AR solutions	NR	NR	NR	✓	✓	NR	NR	✓	NR

NR = not reported

Source: own elaboration

Respondents noted that Big Data enhances marketing decisions through customer segmentation, machine learning, and process optimization. Decisions based on Big Data include "grouping customers and creating offers for them" (Gama). In the automotive sector, it aids market opportunity identification and production monitoring. VR/AR technologies enable quick adaptation of market innovations and compatibility checks with existing products. As noted by Zeta, "market innovations can be easily adapted and checked for compatibility with our products." In the furniture sector, VR is fundamental: "Thanks to VR, the client can immediately check and see how it looks in their home" (Eta). In the automotive industry, "VR/AR allows for better planning and cost optimization, which affects the ability to respond quickly to market changes" (Sigma). The success of VR implementations depends on engaging, high-quality consumer experiences and seamless interactions, which are crucial across industries (Raji et al., 2021).

Strategic entrepreneurship, encompassing innovation, cooperation, and entrepreneurial culture, is strongly supported by IoT/M2M and industrial robotics (Table 4). IoT enables real-time data collection and analysis, forming the foundation for innovation and trends in development. As Gamma noted, "IoT creates intelligent spaces where technology and systems interact seamlessly" (Sestino et al., 2020). Similarly, Alpha stated: "Those who are involved know that IoT can be turned into new ideas and solutions." M2M enhances operational efficiency by enabling precise tracking of resources: "In logistics, it supports telemetry during transport and localization" (Sigma).

Table 4. **The impact of technology on strategic entrepreneurship**

Attributes of strategic agility / Industry 4.0 technologies	Strategic entrepreneurship								
	FOOD INDUSTRY			FURNITURE INDUSTRY			AUTOMOTIVE INDUSTRY		
COMPANY	Alpha	Beta	Gamma	Zeta	Eta	Kappa	Lambda	Sigma	Omega
3D printing/3D scanning	NR	NR	✓	✓	NR	✓	NR	✓	NR
IoT/M2M	✓	NR	✓	NR	✓	NR	NR	✓	NR
AI	NR	NR	NR	NR	NR	NR	NR	NR	NR
Cloud computing	✓	NR	NR	NR	NR	NR	NR	NR	NR
Smart, mobile devices, smart, mobile apps	✓	NR	✓	NR	NR	NR	NR	NR	NR
Industrial robotics, incl. collaborative robots	✓	✓	NR	NR	✓	✓	✓	NR	NR
Advanced BI solutions	NR	NR	✓	NR	NR	NR	NR	NR	NR
Advanced data analytics / Big Data	NR	NR	NR	NR	NR	✓	NR	NR	NR
Blockchain technology	NR	NR	NR	NR	NR	NR	NR	NR	NR
VR/AR solutions	NR	NR	NR	✓	✓	NR	NR	NR	NR

NR = not reported

Source: own elaboration

Automation and robotics, beyond increasing efficiency and reducing costs, foster an entrepreneurial culture by encouraging employee engagement. Interestingly, some managers seemed more enthusiastic about robotics than AI, possibly because of its more immediate, tangible benefits. As Beta noted, "employees want to develop and are open to new solutions and ideas." Similarly, in the food industry, automation "offers a great perspective and development opportunity" (Alpha). In the furniture sector, automation supports multifunctionality and openness to innovation, as Kappa observed: "New technologies not only do not exclude employees but enhance their multifunctionality." Moreover, employees recognize how technological advancements improve efficiency, which is reflected in their paychecks (Kappa). Automation also strengthens collaboration with partners. As Eta stated, "If you want to work with us, you need to meet our standards to collaborate." This alignment drives partner development and supports innovation. In

the automotive industry, companies work on "solutions and machines that will carry out entire processes independently," enabling innovation and growth (Lambda). In the furniture industry, 3D and VR/AR technologies play a significant role in enhancing strategic entrepreneurship. These tools improve collaboration by streamlining decision-making and facilitating experimentation. As Zeta noted, "Thanks to 3D technology (…) we can more easily cooperate on components, designs for a client." VR technology further supports collaboration: "Virtual reality aids collaboration with partners on every level, allowing us to quickly check if, for example, holes will fit to the overall design" (Zeta). These technologies also foster a culture of innovation and creativity. As Kappa observed, "3D/VR technologies enable the realization of seemingly impossible ideas, positively impacting people's creativity and drive to optimize tasks." In the automotive sector, 3D printing encourages rapid prototyping and experimentation, facilitating collaboration and testing.

The **flexibility attribute** benefits most from Industry 4.0 technologies, as nearly all examined solutions enhance operational adaptability (Table 5). For instance, IoT/M2M enables "communication between conveyors of different production lines," reducing process errors (Beta). Additionally, these technologies "show a significant advantage over humans – they do not get tired... when a person sees hundreds or thousands of boxes daily, they can no longer cope" (Alpha). The automotive industry highlights the role of IoT and communication technologies in optimizing processes and reducing errors:

Table 5. **The impact of technology on flexibility**

Attributes of strategic agility / Industry 4.0 technologies	**Operational flexibility**								
INDUSTRY	**FOOD INDUSTRY**			**FURNITURE INDUSTRY**			**AUTOMOTIVE INDUSTRY**		
COMPANY	Alpha	Beta	Gamma	Zeta	Eta	Kappa	Lambda	Sigma	Omega
3D printing/3D scanning	✓	NR	NR	✓	✓	✓	NR	NR	✓
IoT/M2M	✓	✓	✓	✓	✓	✓	NR	✓	✓
AI	NR	NR	NR	NR	NR	NR	NR	NR	NR
Cloud computing	✓	✓	✓	NR	✓	✓	NR	✓	✓
Smart, mobile devices, smart, mobile apps	✓	NR	NR	NR	✓	NR	NR	NR	NR

Industrial robotics, incl. collaborative robots	✓	✓	✓	NR	✓	✓	NR	✓	✓
Advanced BI solutions	NR	NR	✓	NR	✓	NR	✓	NR	NR
Advanced data analytics / Big Data	NR	✓	✓	NR	✓	NR	NR	NR	✓
Blockchain technology	NR	NR	NR	NR	NR	NR	NR	NR	NR
VR/AR solutions	✓	✓	NR	✓	✓	NR	NR	NR	NR

NR = not reported

Source: own elaboration

"IoT and communication technologies optimize processes by avoiding, for example, production errors" (Sigma). These technologies enhance flexibility through real-time monitoring, enabling quicker responses to breakdowns and maintenance needs (Omega). IoT and M2M also streamline operations by improving accuracy and reducing costs. As Kappa noted, "this includes digital product execution records sent from office computers to directories in each machine," which shortens operation times. Other impactful technologies include cloud computing and automation. As Alpha emphasized, "managing a fleet of robots is much easier than managing a team of people, accelerating processes and eliminating bottlenecks." Similarly, Beta noted, "Robots and automation enhance our product quality."

Cloud computing supports operational flexibility by enabling scalable IT resource management and enhancing data security. As Gamma explained, "without this solution, we would have to set up servers and server rooms, likely increasing costs." Big Data further boosts flexibility by identifying and responding to production problems in real-time: "Data analysis allows for quick responses to production problems, increasing operational flexibility" (Omega). VR and AR technologies offer additional benefits, such as remote service capabilities and machine adjustments. Beta highlighted that "technicians can remotely connect with an employee in the company to see what is happening with the machine and guide the process." Similarly, Alpha described how "one person physically intervenes with the machine, while another from the manufacturer's support in India provides guidance". In the furniture sector, 3D printing and VR/AR technologies significantly support flexibility. As Zeta noted, "We can use different construction mechanisms (…) make product modifications relatively quickly, faster than the competition." 3D printing also reduces downtime by enabling the production of spare parts, while VR enhances the sales process:

"Thanks to VR, customers can immediately check and see how the furniture looks in their home" (Eta).

Respondents noted the weakest connections between Industry 4.0 technologies and **strategic leadership**. Among the surveyed companies, only one (Gamma, from the food industry) identified a direct connection between Industry 4.0 technologies and strategic leadership, highlighting the potential of tools like smart applications and business intelligence to support leadership by engaging employees. In the context of strategic agility, leadership plays a critical role in driving change and ensuring the organization's adaptation to its dynamic environment. Effective leaders not only implement necessary changes but also inspire teams by appealing to their emotions and motivating them to achieve more. Strategic leadership also involves fostering a culture of learning, where employees' ideas and knowledge are actively utilized. However, only one company in the food industry explicitly linked Industry 4.0 technologies to leadership development, noting that tools such as smart applications and business intelligence—frequently used in daily operations—can enhance employee engagement and indirectly support leadership goals by fostering a motivated and proactive workforce.

5. Discussion

We propose an integrated model linking management theories with strategic agility attributes, enhanced by Industry 4.0 technologies (Figure 2). Technologies such as AI, IoT, robotics, and 3D printing are key enablers of adaptive capabilities. Figure 2 illustrates how these technologies enhance strategic agility by supporting attributes like strategic sensitivity, operational flexibility, and entrepreneurship, forming the foundation for 'smart' strategic agility – a technology-driven capability that empowers organizations to adapt flexibly and innovatively to dynamic market conditions.

Advanced data analytics and Big Data enhance strategic sensitivity by enabling rapid and accurate responses to market changes. These technologies align with the dynamic capability theory (Teece et al., 1997) and improve decision-making by identifying and assessing opportunities (Mikalef et al., 2019). Similarly, Sajdak et al. (2022) confirm their effectiveness in predicting and responding to industry disruptions. AR/VR-assisted applications further contribute to these capabilities by improving productivity, reducing errors, and enhancing design processes (Eswaran & Bahubalendruni, 2022).

Building on this foundation, we found that IoT/M2M and robotics support strategic entrepreneurship by fostering innovation and collaboration through real-time data collection. It's worth noting, though, that some managers expressed concerns about the complexity of integrating these technologies into their existing systems. We found that this aligns with the resource-based view (Barney, 1991) and Makarius et al. (2020), who emphasize technology's role in fostering entrepreneurial culture. However, the limited

role of cloud computing in enhancing collaboration with business partners suggests that its application may be constrained by industry-specific factors, such as data security concerns or infrastructure limitations.

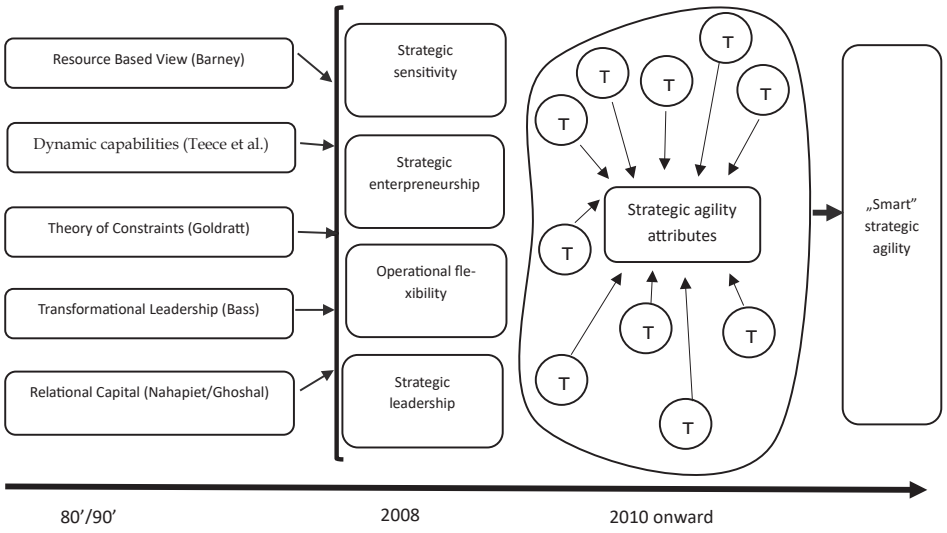

Figure 2. **Industry 4.0 technologies as stimulators of strategic agility attributes**

T = one of Industry 4.0 technologies, e.g. AI, advanced robotics, IoT, cloud computing, BI solutions, 3D printing/scanning

Source: own elaboration

Automation, IoT, and cloud computing enhance operational flexibility by optimizing production, reducing errors, and improving efficiency. These technologies support quicker adaptation to market demands, aligning with findings by Rajput & Singh (2019) and Ballestar et al. (2020). Nevertheless, our findings suggest that their effectiveness may vary depending on organizational readiness and the maturity of technological adoption.

While the impact of Industry 4.0 technologies on leadership is limited, human capital remains central. While technologies are undoubtedly helpful, they fall far short of replacing human intuition. This aligns with Faruquee et al. (2021), who emphasize that technologies like ERP often outperform AI or blockchain in building trust, which is a cornerstone of effective leadership.

Our study demonstrates how Industry 4.0 technologies support dynamic capabilities by enabling faster and more precise market responses. Advanced data analytics and Big Data facilitate continuous monitoring, enhancing strategic sensitivity. Extending the resource-based view (Barney, 1991), we show that IoT/M2M and robotics create valuable resources that drive innovation and collaboration. We contribute to transformational leadership (Bass, 1985) and relational capital (Nahapiet & Ghoshal, 1998) by highlighting the complementary roles of human and technological resources. This underscores the importance of balancing technological advancements with human-centric leadership approaches. Our findings fill a gap noted by Piccarozzi et al. (2018) on Industry 4.0's impact on strategic agility attributes. Expanding dynamic capabilities theory (Teece et al., 1997), we show that technologies like IoT and Big Data enhance perception and accelerate resource reconfiguration. Nonetheless, strategic leadership remains rooted in human and relational capital (Bass, 1985; Nahapiet & Ghoshal, 1998), emphasizing the ongoing importance of human factors.

6. Conclusions, managerial implications, and future research directions

Our study demonstrates how Industry 4.0 technologies, such as IoT, 3D printing, advanced data analytics, and VR/AR, enhance strategic agility in manufacturing companies. These technologies support dimensions of agility, including strategic sensitivity, entrepreneurship, operational flexibility, and leadership. By adopting tailored applications of these technologies, companies benefit from improved operational efficiency, faster innovation, and better market adaptability, strengthening their competitive edge and long-term sustainability.

The research highlights managerial implications, emphasizing the importance of leveraging Industry 4.0 technologies to navigate market variability and uncertainty. Advanced data analytics and Big Data enhance strategic sensitivity through real-time monitoring and rapid responses, aligning with the dynamic capabilities framework (Teece et al., 1997). IoT and robotics foster entrepreneurship by driving innovation and collaboration, while automation improves operational flexibility by optimizing production processes. Managers should prioritize skill development in areas such as data analytics, ERP system integration, and digital collaboration tools, while fostering soft skills like transformational leadership and team collaboration in digital environments. Technologies like AI and ERP support leadership but cannot replace the human aspects of vision and inspiration, emphasizing the continued importance of transformational leadership (Bass, 1985) and relational capital (Nahapiet & Ghoshal, 1998).

Interestingly, our findings reveal a striking paradox - while Industry 4.0 technologies significantly enhance operational and strategic dimensions of agility, their impact on leadership remains constrained. This could be because leadership effectiveness depends

on uniquely human factors, such as intuition and emotional intelligence, which no technology can fully replicate. In this sense, technology's transformative potential is both an enabler and a limitation, as leadership effectiveness continues to hinge on uniquely human capabilities.

Our study has some limitations that suggest avenues for further research. First, its focus on manufacturing companies in Poland may limit the applicability of findings to other countries and industries. Second, qualitative methods, such as in-depth interviews with senior managers, may introduce biases, underscoring the need for complementary quantitative research. Third, the study concentrates on select technologies, leaving room to explore the broader range of Industry 4.0 solutions. For example, further studies could examine the impact of technologies like blockchain or quantum computing on agility attributes.

Future research should expand to sectors beyond manufacturing, such as healthcare, finance, and retail, to identify sector-specific applications and challenges. Investigating how Industry 4.0 technologies influence organizational culture could offer insights into fostering innovation and agility. Longitudinal studies are also needed to assess the evolving integration of these technologies and their sustained impact on strategic agility. In the long term, future advancements in next-generation AI could reshape the dynamics of strategic agility, offering new pathways for innovation and adaptation.

Authors' contribution

M.S. and **M.M.:** article conception, theoretical content of the article, research methods applied, conducting the research, data collection, analysis and interpretation of results, draft manuscript preparation.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used *Claude* in order to check references *(APA7 style).* After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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