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Industry 4.0 Ecosystems: Lessons from three Polish industrial regions

Abstract: This paper analyses how Industry 4.0 (I4.0) and related forms of digital entrepreneurship are embedded in the innovation policies and ecosystems of three Polish industrial regions (NUTS2): Dolnośląskie, Śląskie and Podkarpackie. Drawing on debates in evolutionary economic geography and innovation ecosystem research, the study combines a review of regional strategies with interviews with policy stakeholders. The findings show distinct regional trajectories. Dolnośląskie frames I4.0 as a smart specialisation. Śląskie integrates I4.0 into a comprehensive transformation agenda. Podkarpackie, despite structural weaknesses, leverages niche specialisations, to advance the I4.0 positioning of its metropolitan area. Across all three cases, ecosystems play a supporting role but remain primarily oriented towards incremental innovation and diffusion of available technologies. Clusters act as key facilitators, yet limited trust, SME conservatism, and dependence on multinational corporations constrain broader innovation dynamics and the emergence of breakthrough initiatives. The study concludes that I4.0 functions as a valuable but context-dependent organising concept for regional innovation strategies. Its effectiveness depends on the interplay of industrial structures, governance arrangements, and ecosystem capacities. Policy implications point to the need for place-sensitive approaches that combine support for incremental SME adoption with stronger incentives and conditions for radical innovation.

Keywords: Industry 4.0, innovation ecosystems, regional innovation systems, Poland

Introduction

The advent of the Fourth Industrial Revolution i.e. Industry 4.0 (I4.0) has triggered intense scholarly debate regarding its transformative implications for regional development, industrial restructuring, and innovation ecosystems. I4.0 technologies – including cyber-physical systems, robotics, artificial intelligence, big data and additive manufacturing – are widely recognised as disruptive forces capable of reshaping regional trajectories of growth and competitiveness (Bailey, De Propris 2019, De Propris, Bailey 2021). The European Union has responded by repositioning cohesion and regional policy towards a more innovation-driven agenda, particularly through Smart Specialisation Strategies (renewed Regional Innovation Strategies), which aim to foster structural change and regional upgrading (Bailey, De Propris 2019). Yet, despite these efforts, persistent disparities across European regions remain, with questions arising as to whether I4.0 creates new opportunities for leapfrogging. Comparative analyses across European regions highlight that the effectiveness of Industry 4.0 implementation depends on differentiated levels of digital preparedness and the density of intermediary organisations (Dyba et al. 2022).

Recent contributions emphasise that the pathways of regional transformation under I4.0 are far from uniform. De Propris and Bailey (2021) identify four potential trajectories – endogenous, hyper-transformative, importation-based, and obsolescence – each dependent on local innovation, docking, and translational capabilities. Such differentiation aligns with evolutionary economic geography perspectives, which stress path dependence and diversification as central mechanisms of industrial change (Balland, Boschma 2021). Patent-based analyses show that the geography of I4.0 knowledge production is highly uneven, with only a limited number of European regions displaying the preconditions to lead in new technological domains (Balland, Boschma 2021). This unevenness reinforces the need for nuanced, place-sensitive policy interventions. This differentiated regional response to I4.0 can also be interpreted through the lens of institutional economics, which stresses how formal and informal rules, governance arrangements, and transaction costs shape incentives, trust, and coordination in complex innovation processes (North 1990, Amin, Thrift 1995, Williamson 2000). From this perspective, regional institutional quality and 'institutional thickness' influence the capacity to mobilise intermediaries, implement enabling regulations and coordinate collective investments that are often required for I4.0 diffusion. This complements evolutionary accounts by specifying how institutional arrangements condition regional actors' ability to recombine existing capabilities into new technological paths.

Parallel to these debates, the ecosystem concept has gained traction as an analytical lens to capture the collaborative dynamics underpinning I4.0. We adopt an innovation-ecosystem perspective because it foregrounds the interdependencies, complementarities, and coordination challenges involved in co-developing and scaling I4.0 solutions. At the same time, we draw on the RIS tradition to anchor these relational configurations in territorially embedded institutional and

organisational conditions – particularly the role of intermediaries and regional institutional capacity (Asheim, Gertler 2009). Building on Moore's seminal idea of business ecosystems, recent literature has differentiated between business, innovation, entrepreneurial, and knowledge ecosystems (Cobben et al. 2022). Within this broader framework, innovation ecosystems have emerged as particularly relevant, highlighting the multilateral and interdependent collaborations required for co-innovation and value creation (Klimas, Czakon 2022). In the specific context of I4.0, innovation ecosystems enable small and medium-sized enterprises (SMEs) to pool complementary resources and co-develop complex solutions that would otherwise exceed their individual capacities (Benitez et al. 2020). Longitudinal evidence suggests that such ecosystems evolve over time, shifting from fund-access structures towards platform-driven models of collaboration (Benitez et al. 2020) with trust being an important and multi-layered factor behind collaborative patterns (Kwiatkowski 2023).

The entrepreneurial dimension of ecosystems has also been linked to I4.0. Kumar et al. (2023) argue that digitalisation and automation fundamentally reshape entrepreneurial ecosystems, redefining the opportunities and barriers faced by new ventures. This resonates with calls for a more systematic classification of ecosystem boundaries and goals, which can clarify their diverse contributions to innovation and regional development (Cobben et al. 2022). Furthermore, Zaevska (2024) demonstrates empirically that I4.0 ecosystems cannot be approached through a one-size-fits-all design: their value creation and impact on regional innovation depends on orchestration mechanisms, funding structures, and technological diversity and geographical focus. Regional case studies confirm that institutional context and policy frameworks strongly condition the adoption of I4.0 technologies, as illustrated by the Finnish South Karelia region, where multilevel governance, ecosystem facilitation, and skills policies were crucial enablers of adoption (Igboanua et al. 2025).

A growing body of literature also addresses the spatial and geographical dimensions of I4.0. Fraske (2022) highlights the need for a multi-scalar understanding of how digitalisation reconfigures value chains, clusters, labour markets and innovation processes, while underlining gaps in integrating I4.0 debates into economic geography. Similarly, Balland and Boschma (2021) provide systematic evidence that I4.0-related technologies occupy peripheral positions in the knowledge space, making regional diversification into these domains both risky and uneven. These findings underscore the importance of agency and institutional capacity in shaping transformation. Indeed, recent conceptual advances in regional innovation studies emphasise a shift from structural perspectives to the role of human agency and change agents in driving sustainable restructuring (Asheim, Grillitsch 2025).

Taken together, these contributions point to several critical insights. First, I4.0 is not a deterministic technological wave but a context-dependent process in which regional legacies, policy frameworks, and ecosystem dynamics interact. Second, while ecosystems provide a powerful heuristic to understand collaborative innovation, their structures and outcomes vary widely, requiring more

comparative empirical research. Third, the geography of I4.0 remains uneven, raising the stakes for lagging regions that may either risk further marginalisation or seize opportunities for niche specialisation.

Thus, the objective of this study is to examine the extent to which the concepts of I4.0 and related forms of digital entrepreneurship are embedded in the innovation policies of Poland's leading industrial regions. Our analysis focuses on three regions located along the country's southern industrial belt: Dolnośląskie, Śląskie, and Podkarpackie. These regions, shaped by their historical legacies of traditional, labour-intensive and heavy industries as well as more recent inflows of advanced manufacturing investments – often stimulated by foreign direct investment (Przeździecka 2024) – emerge as critical locations of I4.0-related activity (Gwosdz et. al. 2022, 2024). Dolnośląskie and Śląskie, with their metropolitan centres of Wrocław and Katowice situated along the Polish East-West A4 motorway, currently represent the most developed industrial hubs. Podkarpackie also along the motorway, but further East, in turn, constitutes an intriguing case: while ranking among the poorest Polish regions in terms of GDP per capita, its capital Rzeszów aspires to position itself as a high-tech cluster at the eastern frontier of the European Union.

The selection of these three regions is thus motivated by their distinct yet complementary roles in Poland's emerging I4.0 landscape. Dolnośląskie has established itself as a hotspot for automation and smart production driven by multinational corporations and strong university–industry linkages. Śląskie, historically the country's industrial heartland, is undergoing an intensive transformation from mining and heavy industry towards diversified advanced manufacturing, primarily based on automotive, making the embedding of I4.0 practices particularly relevant for regional resilience (Micek et al. 2022). Podkarpackie, although structurally weaker in terms of economic indicators, has successfully specialised in aerospace and high-tech manufacturing around Rzeszów, demonstrating how peripheral regions can leverage niche specialisations to enter the I4.0 domain (see i.a. Suwala 2018). Taken together, these three cases provide a comparative spectrum, offering valuable insights into the differentiated embedding of I4.0 within regional policy frameworks.

Against this backdrop, the study addresses three guiding research questions – in relation to the three regions under scrutiny:

RQ1. What is the scope and alignment of I4.0 references in formal regional policy documents?

RQ2. What principles shape the functioning and spatial patterns of I4.0 ecosystems at the regional level?

RQ3. What is the current significance of the I4.0 concept in regional economic policy?

Materials and Methods

To answer these questions, we adopted a two-step methodological approach combining documentary analysis and qualitative inquiry.

First, a desk review was conducted for three key policy documents in each region: (i) the Regional Development Strategy, (ii) the Regional Innovation Strategy (RIS3 / Smart Specialisation Strategies), and (iii) the Detailed Description of Priorities for the regional operational programme allocating EU funds (ERDF, ESF+ and JTF in case of Dolnośląskie and Śląskie). Each document was systematically analysed to identify and tag content referring to I4.0 across four thematic categories: (i) jobs of the future, (ii) entrepreneurship and start-ups, (iii) diffusion of innovation and technology transfer, and (iv) cooperation within the regional innovation system. The categories were drawn by the authors upon the screening of I4.0 policy documents in Europe, especially in Poland.

In addition, the study drew on a authors' database of Industry 4.0 technology and solution providers, developed as part of a broader research project, which identified over 1,200 entities operating across Poland. The database served as a proxy for mapping the spatial footprint and concentration patterns of I4.0-related business activity, offering contextual evidence on the geographical embeddedness and cohesion of regional innovation ecosystems.

Second, 20 in-depth interviews (IDIs) with business and policy stakeholders were carried out to delineate the boundaries and characteristics of I4.0 ecosystems in the three regions. Following Cobben et al. (2022), the interviews invited respondents to reflect on competitive advantage, geographical and temporal scope, orchestration patterns, actor constellations, ecosystem structure, as well as mechanisms of value creation and capture. The same IDIs further explored the dominant types of innovation and cooperation patterns within the ecosystems (Klimas, Czakon 2022), the current perceived relevance of I4.0 for the regional innovation landscape, expected scenarios for future development, and emerging thematic priorities that have gained prominence in year 2025. Transcripts were obtained with the Stenograf software and content tagging was automated with NotebookLM.

Findings

Desk review

An analysis of regional policy documents across Dolnośląskie, Podkarpackie and Śląskie reveals a differentiated picture of how I4.0 has been integrated into strategic frameworks, innovation agendas, and operational funding priorities. While each region acknowledges the importance of digital transformation and automation, the depth, consistency, and operationalisation of the I4.0 concept vary considerably.

In Dolnośląskie, the overarching regional development strategy (Strategia1 2018) does not explicitly reference I4.0, nor does it formulate measures directly aligned with this model. This absence must be contextualised by the document's age – over seven years old and undergoing revision – which partly explains the lack of explicit I4.0-related content. Nevertheless, the strategy does touch upon elements aligned with the paradigm, particularly through its emphasis on "smart reindustrialisation" achieved by digitisation and automation of both technological and managerial processes in enterprises. A clearer and more deliberate approach emerges in the Regional Innovation Strategy (Dolnośląska 2021), which explicitly frames the transformation of the regional economy in line with I4.0 as a development opportunity. The strategy goes so far as to describe the cybernetic revolution associated with I4.0 as a key challenge for the entire innovation system in the coming decade. One of its operational goals explicitly promotes digital transformation and advanced process automation. Furthermore, the strategy elevates I4.0 to the status of a horizontal smart specialisation, demonstrating its cross-sectoral importance. At the operational level, references to I4.0 appear in several parts of the regional operational programme (Fundusze1 2022), particularly within social priorities. Yet, this presence is fragmented, consisting of scattered measures rather than a dedicated scheme. Notably, SME investments in I4.0-compatible business models are only eligible through debt instruments, rather than direct grants. Overall, Dolnośląskie's I4.0 agenda finds its strongest expression in the innovation strategy, where it is incorporated diagnostically, analytically, and strategically. The recognition of I4.0 as a separate smart specialisation highlights its elevated position within the region's development model.

In Śląskie, the principles of I4.0 are prominently embedded in regional development documents, reflecting the region's need to reinvent its traditional industrial economy. The development strategy (Strategia2 2020) outlines economic transformation through initiatives designed to automate, flexibilise, and digitise business operations, while simultaneously enhancing workforce skills. I4.0 here is viewed as a vehicle to diversify and increase the competitiveness of the regional economy. The Regional Innovation Strategy (Regionalna1 2021) rests on a comprehensive diagnosis of the I4.0 ecosystem, explicitly naming digital transformation as one of the primary development challenges. This challenge is operationalised through a hierarchy of objectives and associated tools, with I4.0 mechanisms directly incorporated into development pathways. Moreover, the strategy identifies flagship projects with the potential to advance I4.0 adoption at scale, signalling an advanced stage of strategic planning compared to other regions. The operational programme (Fundusze2 2022) provides support for SMEs seeking to digitise and automate their processes, while also addressing human capital needs by offering upskilling opportunities for employees. These measures are intended to ensure that firms not only adopt new technologies but also acquire the competencies necessary to sustain them. The I4.0 agenda extends beyond the core strategic and innovation documents, appearing also in the Śląskie's Economic Development Policy 2030 (Polityka 2022). While this latter reference is limited to diagnostic and analytical observations, it reflects the pervasive presence of the

I4.0 theme across the region's policy landscape. In practice, the operational focus is on SME transformation and aligning workforce competencies with emerging I4.0-driven labour market shifts.

In Podkarpackie, the integration of I4.0 into strategic policy is even more explicit. The regional development strategy (Strategia3 2020) directly identifies industrial transformation as a central course of action, linking it to education, firm-level business models, and the strengthening of regional networks. Here, the I4.0 agenda is woven into a broader competitiveness framework grounded in innovation and modern technologies. The Regional Innovation Strategy (Regionalna2 2022) goes a step further by framing "the evolution of the regional economy towards I4.0" as a cross-cutting objective. Within this framework, the model is embedded as a guiding principle for the entire regional innovation system. Implementation responsibilities are distributed across the quadruple helix of stakeholders: regional government, enterprises, academia, and society. This allocation underscores the expectation that I4.0 is not the domain of one actor but rather a collective commitment across the ecosystem. On the operational programme level (Fundusze3 2022), SME grants are available for research and innovation projects aimed at developing new products, services, and production processes consistent with "I4.0 appropriate solutions." The regional scheme, however, only partially addresses digitalisation; its limitations are somewhat mitigated by the European Funds for Eastern Poland 2021–2027 (Fundusze4 2022), a supra-regional programme that provides comprehensive support for SME transformation through automation and robotisation. Consequently, Podkarpackie stands out for its strong strategic orientation towards I4.0, where the model is not only a horizontal determinant but also articulated through specific actions and stakeholder roles.

Taken together, these findings reveal a spectrum of approaches to embedding I4.0 into regional policy. Dolnośląskie demonstrates strong strategic alignment through its Regional Innovation Strategy, though operationalisation remains fragmented and primarily reliant on financial instruments. Śląskie positions I4.0 as central to its economic transformation agenda, articulating a clear strategic framework, diagnosing its ecosystem comprehensively, and linking objectives to flagship projects and workforce development. Podkarpackie integrates I4.0 systematically across strategic levels, treating it as a horizontal determinant of development and explicitly involving all quadruple-helix stakeholders, while complementing regional measures with supra-regional funds. The comparative picture thus underscores both the differentiated regional pathways and the shared recognition that I4.0 constitutes a critical determinant of long-term competitiveness and innovation in Poland's industrial regions.

In-depth interviews

The in-depth interviews point to several common assessments of the boundaries and characteristics of I4.0 ecosystems in the three regions (based on the structure proposed by Cobben et al. 2022). Regional I4.0 ecosystems demonstrate

differing levels of maturity and stability. Dolnośląskie is perceived as a region developing in an organic way, supported by relatively high standards of governance, yet these achievements are not widely publicised or promoted as success stories. Respondents suggest that Dolnośląskie may lack a strong brand identity comparable to Śląskie, where the Silesia Automotive & Advanced Manufacturing (SAAM) cluster has successfully established itself. In contrast, the evolution of the I4.0 ecosystem in Podkarpackie is evaluated as the weakest, shaped by structural constraints and heavily dependent on available funding: "In Podkarpackie this is very much pushed. The development of the ecosystem is forced, resulting from access to large financial resources. Fortunately, these funds are used quite sensibly."

Clusters, or more precisely cluster initiatives, emerge as the most important undertakings animating I4.0 ecosystems, providing the basic structures and incentives for collective action. Beyond SAAM in Śląskie, relevant roles are played by the Aviation Valley and the Eastern Automotive Alliance (WSM) in Podkarpackie and the automotive and aerospace clusters orchetrsated by the Legnica Special Economic Zone (Dolnośląskie). Although clusters are commonly described as bottom-up initiatives, interviewees emphasised that they were all, to varying degrees, also "pushed" by public institutions. This reflects a wider context in which persistent deficits of trust and limited skills in collaboration remain structural weaknesses in Polish business environments.

When it comes to clear objectives and adequate structures, the system of public support – particularly its financial dimension – is the subject of significant criticism. National policy and EU funding programmes are widely perceived as poorly designed and insufficiently adapted to a dynamically changing environment. Many entrepreneurs, discouraged by bureaucracy and lengthy reporting procedures, expressed pessimism about relying on these resources. As one respondent explained: "A huge amount of energy goes into administration and consulting, which means that a lot of resources are not used for authentic development." Instruments such as the National Key Clusters programme often misalign with the specificity and ambitions of clusters. Eligibility criteria are described as arbitrary and administrative, which leads to projects being written "to fit indicators" rather than to meet real needs.

A significant challenge repeatedly emphasized by respondents was the low efficiency and instability of the national policy framework for supporting the digital transformation of industry. The Poland Platform for Industry of the Future, established in 2019, and the Regional Councils, operating since 2020–2021 under its umbrella, have not yielded the expected outcomes. As a result, from 2025 onward the competencies of the institution meant to orchestrate national actions toward Industry 4.0 have been assumed by the Polish Agency for Enterprise Development (PARP). A renewed dynamism of action is now more eagerly anticipated from the regional institutions clustered around EDIHs (European Digital Innovation Hubs), which only began to function in earnest in 2024. Despite these challenges, regional I4.0 ecosystems do provide platforms for launching projects, albeit on a limited scale. Activities often concentrate on exchanging

good practices and optimising processes. The SAAM cluster has been especially active, offering the "SME Go Digital" service, a mobile I4.0 demonstration centre, and a virtual factory in cooperation with technology providers. The WSM cluster has set up think-tank groups to facilitate knowledge transfer from large companies to SMEs and has also initiated the Podkarpackie Automotive Academy, which engages teachers and students in internships. Nevertheless, regional or sub-regional initiatives frequently encounter difficulties. Large companies tend to be reluctant to share know-how about I4.0 implementation, except in cluster-led workshops. Even in critical areas such as cybersecurity, there is often no clear demand for training or collaboration.

A structural dualism also emerges in the ecosystems, dividing large corporations from SMEs. The size of the enterprise appears to be the main fault line shaping openness to I4.0. While large corporations typically have established digitalisation strategies and a stronger determination to invest, SMEs approach I4.0 with caution. Rather than signalling reluctance per se, the passive posture of many small firms was interpreted as a survival strategy: numerous SMEs are micro-enterprises with constrained cash flow and capabilities, and without sufficiently accessible support instruments, they tend to avoid innovation risks. Clusters increasingly include technology providers, whose numbers are growing rapidly and sometimes equal those of manufacturing firms. Service firms such as integrators and knowledge providers are also expanding around digitalising corporations. These integrators often originate as small firms with academic or applied backgrounds and have gained experience through ad hoc projects for large companies.

Relations with the research sector are initiated through activities such as science-to-business meetings or the creation of dedicated university curricula. Yet respondents consistently stressed the lack of a common language and mutual understanding between industry and education: "Firm owners do not speak the same language as IT specialists." "Which language should be used so that IT specialists understand the needs of the company, its perspective on processes?"

Ecosystems have contributed to real economic initiatives that enhance competitiveness, mainly through knowledge transfer and process optimisation. However, the diffusion of I4.0 into industry is not necessarily dependent on the vibrancy of regional ecosystems but rather on structural pressures to optimise costs and maintain high, repeatable quality in response to the growing demands of global clients. Techniques such as augmented and virtual reality (AR/VR), digital twins, and AI-supported quality control are introduced as successive steps in competitiveness enhancement. For SMEs and local subcontractors, competitiveness often depends on integrators that build tailor-made, innovative machines and solutions enabling firms to operate "smarter and cheaper." Yet these linkages are frequently shaped by the requirements of large corporations: "Some things are definitely imposed. They are imposed by end customers." Multinationals often oblige suppliers to use digital systems such as EDI or traceability, which, though costly for smaller firms, accelerate digitalisation.

The ability of ecosystems to retain value added within the region is widely regarded as limited. While there are aspirations to increase reliance on local suppliers, the critical transformation from component production to proprietary product development remains embryonic. As one interviewee observed: "We have many firms with very modern production methods. But we also have firms with very traditional methods, which do not change even when orders come from American military bases." Ineffective use of public innovation funds, absorbed by administration rather than authentic development, weakens the retention of capital and talent. SMEs' preference for purchasing expensive, established German or Italian machines rather than working with smaller local integrators further constrains the potential for maximising local value added.

In terms of innovation patterns (based on the structure derived from Klimas & Czakon 2022), the prevailing paradigm is evolutionary rather than revolutionary. The dominant forms are incremental innovations – adaptations, modifications, or extensions of existing solutions. This orientation reflects several structural factors. The first is the continuous pressure for process optimisation, particularly in the automotive industry, which has historically focused on relentless efficiency improvements. I4.0 technologies are thus absorbed as the next stage of this optimisation trajectory, reinforced by the increasingly stringent demands of global clients. Second, decision-making and scale pose constraints. Product innovation, and particularly radical product changes, typically fall under the remit of multinational headquarters rather than Polish subsidiaries, limiting the regional scope for breakthrough innovations: "These technologies are developed elsewhere, decisions on what will be produced are taken outside Poland – unfortunately not in the Polish branch. This may be a barrier for firms that want to advance." Once again, as for SMEs, their preference to buy established foreign solutions rather than experiment with local providers shall be highlighted.

The dominant form of cooperation in I4.0 ecosystems is therefore oriented toward the adoption and diffusion of available technologies and knowledge transfer, with clusters serving as the primary platforms. As one respondent emphasised: "The transfer of knowledge from more global firms to SMEs cooperating with us [the cluster] – to raise their level – is absolutely justified." Integrators play a central role in creating value, focusing not on inventing new technologies but on implementing them in tailored ways that allow firms to compete more effectively. Research and development cooperation remains marginal. Companies cite barriers such as bureaucracy, overhead costs, and the absence of a common language with universities. Global corporations are generally unwilling to share information for joint product development, and fears of competition inhibit broader collaboration: "I am surprised by this toxicity, the fear of competition, the unwillingness to talk about one's solutions." – noticed one of the respondents.

Thus, cooperation is largely oriented toward optimising internal value chains rather than engaging in joint research or market expansion. Ecosystem initiatives are predominantly adaptive and educational, not research-intensive or expansionary. Policy support for I4.0 is increasingly viewed as outdated, yet it remains a central strategic element within regional innovation systems, consistent

with earlier document analysis. Stakeholders, particularly policy programmers, stressed that such measures are not a mere "fashion" but reflect close collaboration with regional actors, noting that thinking along these lines pre-dated the rise of I4.0 as a popular slogan. Policy instruments typically target incremental innovation aimed at maintaining competitiveness in supply chains, a focus broadly aligned with the development capacities identified by cluster actors. At the same time, this convergence implies a persistent absence of breakthrough innovations across the regions.

The most likely scenario for regional trajectories combines dynamic technological advancement by large corporations – driven by market demand – with persistent conservatism among SMEs and ongoing difficulties in ecosystem collaboration. Multinationals are expected to continue implementing I4.0 solutions, obliging their suppliers to follow suit. Some SMEs, previously able to sustain themselves as subcontractors for foreign markets, especially Germany, remain reluctant or unable to invest in innovation. As one respondent put it: "On the one hand we have this ambition of soon having artificial intelligence, quantum computing, Industry 5.0 and so on. On the other hand, when we analyse the reality in the region, we see a large sector that generates a lot of GDP but is often not as technologically developed as we would like."

Finally, the interviews revealed that while automation and digitalisation remain crucial, the terminology and priorities are shifting. Over recent months (fieldwork concluded in July 2025), respondents observed three emerging themes. First, artificial intelligence has entered the discourse, reshaping existing I4.0 solutions and partly displacing the concept as a leading frame. Second, green technologies and energy are gaining prominence, closely linked to automation and robotics but increasingly shaped by the debates over the tensions between climate policies (once the European Green Deal) and competitiveness struggles. Third, the concept of Industry 5.0 appears sporadically in documents and discussions, though respondents remain uncertain whether it will ever achieve the prominence of I4.0. In 2025, defence and security have also emerged as new strategic frames for European industrial resilience, drawing attention away from I4.0.

Regional differentiation and spatial cohesion of I4.0 innovation ecosystems

Complementing the qualitative findings from interviews, the spatial analysis of I4.0 technology and solution providers reveals pronounced intra-regional asymmetries in the configuration and cohesion of innovation ecosystems. Across the three analysed regions, distinct spatial logics emerge – ranging from highly concentrated metropolitan systems to more polycentric or dual-core configurations (Fig. 1). These patterns reflect not only the historical trajectories of industrial development but also the differentiated capacities of regional institutions to extend innovation linkages beyond metropolitan cores.

In Dolnośląskie, the ecosystem displays a marked concentration of I4.0 suppliers within the Wrocław Metropolitan Area, which accounts for approximately 88.5 per cent of all identified firms. This dominance justifies describing Wrocław as an "innovation island" within the regional landscape. The key institutions of the ecosystem – the Wrocław Technology Park, the Wrocław University of Science and Technology, and the Wrocław Agglomeration Development Agency – are all anchored within the metropolitan area and operate largely with a local orientation. Although several sub-regional centres such as Wałbrzych, Legnica, Polkowice, Jelenia Góra and Świdnica host medium- and high-tech industries receptive to digital transformation, these locations lack the critical mass of suppliers or institutional depth required to form self-sustaining clusters. One likely reason lies in the limited embeddedness of large, export-oriented external firms and the absence of strong academic branches or research facilities outside the metropolis that could anchor technologically advanced entrepreneurship. The result is a pronounced metropolitan dominance coupled with a fragmented peripheral ecosystem.

In Śląskie, around 68 per cent of I4.0 suppliers are located within the Upper Silesian Metropolitan Area (GZM), reflecting a more polycentric metropolitan structure centred around Gliwice and Katowice, with Bielsko-Biała in the south emerging as a secondary growth pole (approximately 11 per cent of suppliers). The region's spatial configuration benefits from dense automotive linkages that span all sub-regions and frequently overlap with Industry 4.0 integrators (Fig. 1). As shown in previous research (Gwosdz et al. 2024), the proximity between automotive firms and technology integrators constitutes a key spatial mechanism facilitating innovation diffusion. Regional policy instruments such as the Katowice

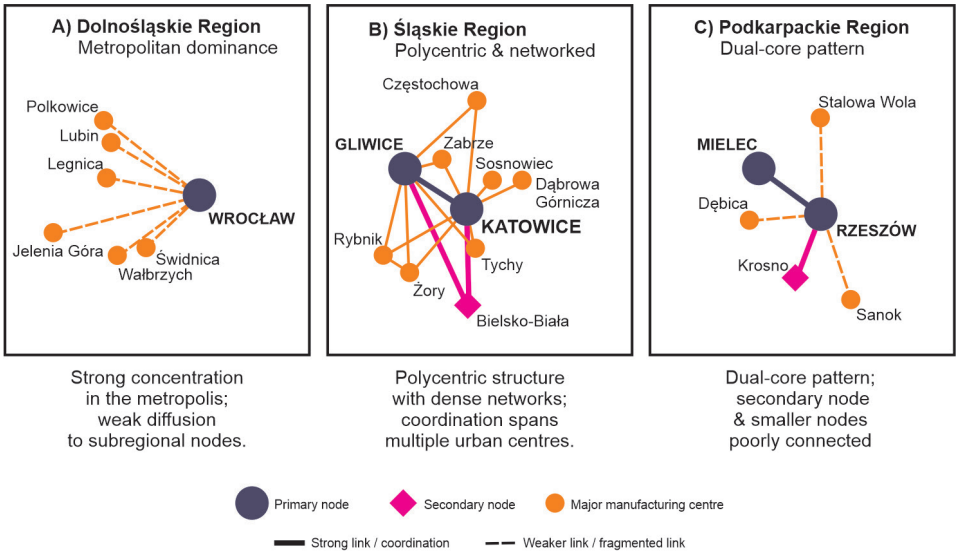

Fig. 1. Three spatial configurations of regional Industry 4.0 innovation ecosystems
Source: Authors' design.

Special Economic Zone and the SAAM cluster play important roles in integrating these distributed activities at the regional scale, enabling coordination across multiple urban centres. In Bielsko-Biała, a strong base of locally rooted IT firms further strengthens regional capacity for digital solutions. Overall, Śląskie exhibits a polycentric and networked ecosystem, sustained by institutional coordination and sectoral synergies.

In Podkarpackie, around 54 per cent of I4.0 suppliers are concentrated in Rzeszów and its functional urban area, with a secondary cluster in Mielec (about 14 per cent) and additional, smaller nodes in Stalowa Wola, Dębica, and Krosno. This configuration forms a dual-core pattern dominated by Rzeszów – the regional capital and hub for aerospace and IT industries – complemented by Mielec as a secondary pole of growth. Mielec exemplifies how a historically developed aviation centre with a diversified medium- and high-tech base (within the Special Economic Zone "Invest-Park Mielec") and a well-established engineering milieu can evolve into a local I4.0 ecosystem. This process is supported by a technology incubator and a strong vocational-training system aligned with I4.0 competences. A smaller node is also developing in Krosno, both in the aerospace sector (in strong connection with the Rzeszów regional node) and in the automotive industry. Nevertheless, the overall number of I4.0 suppliers in Podkarpackie remains substantially lower than in Dolnośląskie or Śląskie, underscoring the peripheral and emerging nature of its ecosystem.

Discussion and conclusions

The analysis of Dolnośląskie, Śląskie and Podkarpackie demonstrates that I4.0 is neither a uniform policy agenda nor a simple technological trend, but rather a context-dependent framework that regions interpret in line with their industrial legacies, institutional capacities and strategic ambitions. In Dolnośląskie, the strongest articulation of I4.0 is visible in the innovation strategy, though operationalisation remains fragmented and reliant on financial instruments. Śląskie embeds I4.0 in a comprehensive transformation narrative, linking it to both cluster development and workforce upskilling. Podkarpackie, while structurally weaker, illustrates how peripheral regions can strategically mobilise I4.0 rhetoric and supra-regional resources to position themselves in niche specialisations.

These differentiated pathways mirror broader debates in the literature. As De Propris and Bailey (2021) note, regional transformation under the Fourth Industrial Revolution may follow several trajectories, from endogenous growth to risks of obsolescence. The three Polish regions might illustrate this spectrum: Śląskie seems to tend towards a hyper-transformative model, Dolnośląskie aligns more with gradual adaptation, and Podkarpackie with an importation-driven approach reliant on external resources. Agency, institutional design and multi-scalar governance play their roles here in shaping outcomes (Asheim, Grillitsch 2025, Igboanua et al. 2025). Our findings resonate with earlier conceptualisation on recent Silesia's transformation, where the co-evolution of the IT and automotive

sectors constituted a "critical conjuncture" enabling the rise of an Industry 4.0 pathway (Micek et al. 2022). A similar dynamic is visible in Podkarpackie, where according to Suwala & Micek (2018) the evolution of the Aviation Valley from a traditional cluster into a regional development platform illustrates a gradual shift from smart specialisation towards cross-sectoral diversification.

A complementary way to interpret these differences is through the notion of territorial capital, understood as a place-specific bundle of tangible and intangible assets that condition collective action and innovation capacity (Camagni, Capello 2013). In this view, social capital and institutional endowment help explain why some regions are better able to mobilise intermediaries, sustain collaboration and translate strategic agendas into coordinated action. Kwiatkowski's (2023) evidence from Polish regions shows that Podkarpackie stands out in terms of both social capital and institutional thickness, which supported broad cluster-oriented development and the consolidation of regional networking structures.

The ecosystem perspective further enriches this understanding. Clusters and collaborative initiatives act as pivotal anchors for I4.0 diffusion, yet their effectiveness is often constrained by limited trust, uneven SME engagement, and persistent dependence on large corporations. In Central and Eastern Europe, these weaknesses are amplified by the low level of inter-organisational trust and the limited degree of institutional thickness that characterise many regional innovation systems (Dyba, De Marchi 2022), reducing their capacity to sustain collective learning and innovation. This observation resonates with broader insights that innovation ecosystems tend to evolve from fund-access arrangements towards platform-driven collaboration, with success hinging on orchestration mechanisms and knowledge diversity (Benitez et al. 2020, Zaevska 2024). Yet, as our interviews revealed, ecosystems in Poland remain primarily adaptive and incremental, reinforcing the view that most regional I4.0 innovation is evolutionary rather than radical (Klimas, Czakon 2022).

At a more general level, the findings suggest that I4.0 in regional policy has already begun to be re-framed. Stakeholders increasingly place emphasis on artificial intelligence, green technologies and, to a much lesser extent, Industry 5.0. This shift reflects a broader transition from an efficiency-driven paradigm – centred on process optimisation and cost competitiveness – towards a resilience-driven model of industrial and regional development. Such a shift seconds broader scholarly calls to embed digital transformation in the wider socio-technical and sustainability transitions shaping European industry (Balland, Boschma 2021, Fraske 2022). The Polish cases therefore highlight not only the promise of I4.0 as a driver of regional upgrading, but also the risks of narrow, technology-centric agendas that overlook evolving strategic priorities.

Beyond inter-regional differences, the analysis also reveals pronounced intra-regional disparities in the spatial cohesion of innovation ecosystems. Such asymmetries limit knowledge diffusion and weaken the territorial embeddedness of innovation networks, reflecting what Fraske (2022) describes as the emerging "geographies of digital transformation". In this context, the recently established European Digital Innovation Hubs (EDIHs) may serve as mechanisms to mitigate

the metropolitan bias of existing ecosystems by extending digital support and experimentation capacities into regional and sub-regional spaces. Whether these organisations can effectively strengthen intra-regional cohesion and bridge the gap between industrial peripheries and metropolitan centres, however, remains an open question and a promising avenue for further research.

In conclusion, I4.0 provides an organising concept for regional innovation policies, yet its impact depends on the interplay between local industrial structures, governance arrangements and collaborative ecosystems. The comparative perspective across three industrial regions of Poland confirms both the opportunities and limitations of the current approach. For policy, the main implication is the need for place-sensitive strategies that balance support for incremental SME adoption with the creation of conditions for more radical innovation. For research, the study points to the value of further comparative analyses of I4.0 ecosystems across different institutional contexts, as well as the necessity to link the debate to emerging agendas on sustainability and resilience.

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Conflict of interest & Authors' contributions

The authors declare that there is no conflict of interest. They declare that the text of the article is entirely their own work. The authors' contributions are as follows:

- Conceptualisation: MB, KG, TK, AS-G,
- Methodology: MB, KG, TK, AS-G,
- Research organisation: MB, KG, TK, AS-G, MH,
- Formal analysis: MB, KG, TK, AS-G, MH,
- Writing: MB, KG, TK, AS-G.

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Ekosystemy Przemysłu 4.0: doświadczenia wybranych polskich regionów przemysłowych

Zarys treści: W artykule przedstawiono analizę tego, w jaki sposób Przemysł 4.0 i cyfrowi przedsiębiorcy wpisują się w politykę innowacji i ekosystemy innowacyjności trzech polskich regionów przemysłowych: dolnośląskiego, śląskiego i podkarpackiego. Na podstawie analiz strategii regionalnych i wywiadów z interesariuszami pokazano odmienne trajektorie ich rozwoju. Województwo dolnośląskie traktuje I4.0 jako inteligentną specjalizację, województwo śląskie – jako element szeroko rozumianej transformacji, a województwo podkarpackie wykorzystuje niszowe specjalizacje. Ekosystemy cechują się innowacjami inkrementalnymi, a ograniczone zaufanie, zachowawczość MŚP i zależność od korporacji osłabiają gotowość do podejmowania radykalnych działań i szeroko zakrojonych inicjatyw. Wyniki badania wskazują na potrzebę terytorializacji polityki wsparcia zaawansowanej produkcji przemysłowej.

Słowa kluczowe: Przemysł 4.0, ekosystemy innowacji, regionalne systemy innowacji, Polska

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