BARRIERS TO THE INDUSTRIAL APPLICATION OF NANOTECHNOLOGIES AT THE FIRM LEVEL

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Abstract

This paper examines the adoption and acceptance of nanotechnologies and advanced materials (NaAM) by firms in old industrial regions (OIRs). Building on the Technology–Organization–Environment framework and the Technology Acceptance Model, the study conceptualizes how technological, organizational, and environmental contexts shape firm-level and individual-level adoption decisions. NaAM offer measurable benefits in durability, energy efficiency, and regulatory compliance, yet their diffusion in OIRs is constrained by legacy infrastructures, path dependence, lock-in effects, and limited absorptive capacity. Complexity and maturity, expressed through Technology Readiness Levels and Manufacturing Readiness Levels together with Environment, Health, and Safety requirements, slow down early adoption and increase reputational and regulatory uncertainty. Organizational conditions, including resources, management support, absorptive capacity, and innovation champions, are pivotal for translating pilot projects into serial production. At the individual level, perceived usefulness, perceived ease of use, and behavioural intention determine the actual use of NaAM solutions, mediated by social influence and facilitating conditions. By integrating these perspectives, the paper provides a theoretical basis for the qualitative studies of NaAM adoption in old industrial regions, underscoring that effective adoption requires alignment of technological, organizational, and environmental enablers with individual perceptions, supported by open innovation, clear intellectual property regimes, and robust regional innovation systems.

Keywords: Nanotechnologies and Advanced Materials, Technology Acceptance Model, Technology–Organization–Environment framework, Old Industrial Regions, case study

INTRODUCTION

Nanotechnology is a multidisciplinary field that deals with the “understanding and control” of matter at the nanoscale of 1 to 100 nm to observe or create nanomaterials with modified properties (1, 2). At this scale, nanoparticles show unique chemical, biological, and physical properties compared to bulk materials, as the increased surface area-to-volume ratio “alters the reactive, mechanical, thermal and catalytic attributes of the materials” (2). These properties — such as enhanced reactivity, improved conductivity, and biocompatibility — open new possibilities for efficiency and sustainability (3, 4). By manipulating materials at the nanoscale, advanced devices and systems are created that foster technological progress (1, 4, 5). Recent studies highlight applications across medicine, sustainable energy, agriculture, environmental protection, and water purification (3), confirming nanotechnology as a revolutionary, expanding, and socially significant field (4). Thus, adoption and social acceptance are crucial to realizing its full potential.

There are several reasons why this paper deals with the acceptance and adoption of nanotechnologies and advanced materials (NaAM) at the firm level in old industrial regions (OIRs). First, NaAM adoption directly shapes firms' investment decisions through measurable gains in product life, energy efficiency, process stability, and regulatory compliance. Second, the prospects of NaAM diffusion and acceptance in OIRs are significantly constrained by the path dependency, cognitive lock-in (6), limited absorption capacity and dominance of medium-low-technology/knowledge-intensive economic activities. Third, it is generally very difficult for the OIRs to develop completely new high-tech industries. However, NaAM can stimulate the diversification into technologically related industries or foster the path upgrading of existing medium-low-tech manufacturing industries: see Calignano and Quarta (2015); Calignano and Jørgensen (2024) (7,8).

The aim of this paper is to provide a theoretical basis for the future qualitative inquiry of the NaAM adoption barriers in OIRs, "industrial districts of the past" that have been experiencing decline due to deindustrialization since the 1970s and early 1990s in post-communist countries (6, 9). Historically, these regions had advanced infrastructure and strong institutional support (Grabher, 1993), but currently they struggle with inefficiency, incompatibility with modern industries and technologies and rigid institutional legacies (10), limiting their global competitiveness (6,9). Examples include Manchester and Lancashire (UK), Saarland (Germany), Lorraine and Alsace (France), Basque Country (Spain), Lower Silesia (Poland), Ústí nad Labem Region (Czechia), Moravian-Silesian Region (Czechia) (9, 11, 12), Rust Belt (USA) or Daegu (South Korea).

NaAM adoption depends on both firm context and individual decision-makers. At the firm level the TOE framework conceptualizes adoption across three domains: Technology (relative advantage, compatibility, complexity, standards, EHS), Organization (resources, structure, absorptive capacity), and Environment (regulation, competition, partners, innovation systems) (11, 13). In OIRs, path dependence and compliance demand heighten the role of all three. The framework is complemented by the Technology Acceptance Model (TAM), which explains individual adoption via perceived usefulness (PU) and perceived ease of use (PEOU), shaping behavioural intention (BI) and use (14, 15). Extensions highlight social influence and facilitating conditions critical to industrial settings (16).

In the next section, the TOE framework for the technology acceptance at the firm level is introduced, followed by the application of the TOE in old industrial regions in the section 2. Section 3 discusses the application of the TAM model in old industrial regions and the final section provides the summary of the models, discussion and conclusions.

1. TECHNOLOGICAL CONTEXT (TOE) AT THE FIRM LEVEL

The TOE (Technology–Organization–Environment) framework explains technology adoption across technological, organizational, and environmental contexts (Tornatzky & Fleischer, 1990) (13). It has become a key model for studies from ERP to AI, often combined with TAM/UTAUT to capture both managerial and user behaviour (11,12). In this study, adoption refers to the transition from pilot use to full-scale production. Key factors include Facilitating Conditions (FC) – standards and compliance (ISO, REACH, EHS), testing access, supply-chain ecosystems, and pilot-line availability – alongside Performance Expectancy (PE), Effort Expectancy (EE), Social Influence (SI), and Innovativeness (INN) (4,11,17,18). In OIRs, obsolete infrastructure and rigid supplier and knowledge networks heighten the role of FC and SI, shaping how PE and EE translate into adoption intentions.

The technological context captures attributes that determine whether, and how rapidly, a firm adopts a solution. These include relative advantage and compatibility, complexity and maturity, piloting opportunities, EHS, standardization, and ecosystem availability (4,11,17,18). For NaAM, adoption further depends on certified materials, property stability under operating conditions, and scalability. Perceived benefits (durability, energy savings, performance) are weighed against perceived risks (toxicology, environmental footprint), directly influencing managerial and supply-chain decisions (2,17,18). Relative advantage and compatibility are often decisive, as added value in performance, quality, efficiency, sustainability, and compliance depends on measurable improvements in final product parameters (4). Complexity and maturity, measured by TRL or MRL, also shape adoption: early requirements for skills, pilot lines, and verification slow uptake due to regulatory and reputational uncertainties (17). Modular rollouts and pilots mitigate such risks by ensuring interoperability and providing reference installations (11). Standardization and compliance mechanisms – REACH, ISO, EHS procedures, certification services – build trust and accelerate mainstream adoption (17,18). Supplier ecosystems and connections to extra-regional networks further support uptake (5). Risk profiles vary by sector, being higher in medicine and food than in engineering, shaping investment choices (17,18). Mapping applications tied to sustainability (energy, water, circular economy) reduces uncertainty and legitimizes investments (3).

The organizational context includes firm size and resources, top-management support, prior experience, absorptive capacity, structure, culture, and compliance systems. In nanotechnologies, adoption also depends on mature EHS and quality systems and on innovation "champions" linking R&D, production, and sales. Evidence shows that clear leadership mandates, internal testing capacity, and cross-functional teams accelerate the adoption (11,19). Resource availability, risk tolerance, and compliance remain pivotal (11). Absorptive capacity depends on staff expertise, internal R&D, and partner ties; interactions between organizational and individual traits shape employees' openness (19). Collaboration with academia is critical, as access to talent and "scientist-entrepreneurs" accelerates knowledge transfer (20). Multidisciplinary teams and structured qualification processes are key for scaling prototypes (11). Established safety protocols for nanoparticles, auditability, and role clarity further enhance trust (17). In OIRs, firms often lack resources, making open innovation with universities essential. Long-term collaborations and clear IP regimes (e.g., projects of the EU Horizon program) facilitate rapid progression from testing to production.

The environmental context comprises competitive and customer pressures, suppliers, regulations, and the regional innovation system. Proximity – technological, geographical, organizational – is decisive, as it enables knowledge sharing and lowers transaction costs (4). Strong networks, including EU nanotech platforms, increase opportunities for testing and scale-up. Conversely, "thin" ecosystems and reliance on a single industry create lock-in and hinder diversification (7,8). Smart specialization and I4.0 programs can foster opportunities but, without alignment to local absorptive capacity, may yield unsustainable "paper projects" (21,22). Public demand in regulated sectors also provides powerful market signals, encouraging investment in safer, higher-performing nanomaterials (23).

2. TOE IN THE CONTEXT OF OLD INDUSTRIAL REGIONS (OIR)

In OIRs, the environment is characterized by path dependence and various types of lock-in (functional, cognitive, political), which increases the probability of the modernization of existing technologies (path upgrading) or diversification into technology-related industries rather than the emergence of completely new technologies, industries or sectors (2). This manifests itself in the environmental context, for example, in lower diversity of industries, markets and potential innovation partners, the rigidity of regional innovation systems, but also in the organizational context, such as process rigidity. In such conditions, the adoption of nanotechnologies is facilitated by a combination of local and extra-regional knowledge, the presence of inter-organizational intermediaries, such as clusters or pilot projects with clear measures of benefits and safety. Last but not least, targeted policies that work with the real capacity of actors and use the public sector as the first user for innovative public procurement (8,29). Positive regional trajectories in the development of nanotechnologies are based on strong cooperation and suitable proximities. The direct influence of geographical and technological proximity on cooperation in European nanotechnology has been empirically proven (4). Specialization in Key Enabling Technologies is spatially concentrated and spreads between neighbouring regions, suggesting the importance of involvement in broader (interregional) networks and smart policy targeting (22).

2.1 Technological component (T) in OIR

In the technological context of TOE, the compatibility of new technology with existing processes and equipment is of key importance. In environments with a high proportion of legacy infrastructure (a set of legacy techno-organizational elements that have been optimized over years for existing materials and processes), companies typically place higher demands on compatibility and have lower tolerance for additional complexity, as this increases integration requirements and change costs. Adoption is facilitated by standardization and interoperability, which reduce perceived risk and integration costs (11). Testing and standards can be another hurdle. In the OIRs, access to testing facilities and certification capacities is often limited, which increases uncertainty about nanotechnologies (EHS, metrology) and lengthens the path from pilot project to production (17,18). An important component is the link to sustainability. Projects with clear benefits for energy, water management, or the circular economy have greater legitimacy in OIR and are more likely to gain the support of management and partners (3).

2.2 Organizational component (O) in OIR

One of the most important components in the organizational context is absorption capacity and presence of champions. The speed of adoption depends on internal capabilities in research and development, employee qualifications, and the presence of a "champion" who connects research and development, production, quality, and sales. In OIR, this role is particularly important due to the inertia of processes (11,19). An important social component is the culture of change and agency. Local culture (e.g., the legacy of a "company town" vs. an entrepreneurially open environment) shapes the willingness to take risks and invest in new technologies. Agency for change rests on the ability of actors to reconnect networks and mobilize assets (24, 26). In all regions, talented and academic inventors are an integral part of development in the OIR. Links with researcher-entrepreneurs and co-inventors from universities accelerate the transfer of knowledge into corporate practice (20).

2.3 Environmental component (E) in OIR

In the environmental component, proximity and networks are important. Technological, geographical, and organizational proximity to universities, application centres, and supply chain lead firms reduces transaction costs and increases the likelihood of collaboration and expansion (4). Weakly connected (“thin”) regional ecosystems – with limited diversity of actors and weak links to extra-regional knowledge flows – increase dependence on existing trajectories and increase the possibility of lock-ins. Therefore, firms are more likely to modernize new or related technologies than enter new technological domains (7,8). Another factor is the complex of barriers of research and innovation cooperation. Different types of barriers prevail in different regions (e.g., knowledge-related barriers vs. institutional barriers), which require targeted measures. Cooperation is further hampered by specific barriers such as asymmetry of expectations or administrative burden (27,28).

Policy instruments such as Industry 4.0 and smart specialization can create opportunities if they respect local absorptive capacity. Otherwise, there is a risk of uneven effects and “islands” of progress that do not change the broader trajectory (21). At the same time, public demand in regulated sectors can act as a market trigger for safer and higher-performance solution (23). Complementing these demand- and policy-side levers, in old industrial regions universities function as global–local pipelines, channelling two-way knowledge flows between the region and global networks; when configured well, these linkages reduce the risk of path dependence and lock-in into local routines (29). The last important factor is the demand logic. In peripheral regions, weaker local demand is compensated for by connections to extra-regional markets. Demand then acts as a "driving force" for the adoption of technologies within companies (23).

3. TAM IN THE CONTEXT OF OLD INDUSTRIAL REGIONS (OIR)

Technologies of NAaM diffuse within firms in OIRs through the everyday decisions of individuals – engineers, process technologists, and managers in quality and procurement. It is therefore appropriate to apply the Technology Acceptance Model (TAM), focused on perceived usefulness (PU) and perceived ease of use (PEOU) as the immediate antecedents of behavioural intention (BI) and actual use (USE) (14,15). In OIRs, organizational and regional influences – cautious culture, rigid processes, and “thin” networks – are also pronounced; hence the model needs to be extended with moderators from the firm and regional environments (4,19).

3.1 Perceived usefulness (PU)

– the extent to which people in the firm believe the new technology will improve their work performance or business outcomes – for example, product quality, yield, process stability, safety, costs, compliance with standards, and customer requirements (14,15). For firms in OIRs, perceived usefulness (in the TAM sense) has a pronounced legitimation function. New solutions gain traction when their benefits are demonstrable against lead-customer specifications, codified standards and regulations, and clear key performance indicators; without such anchoring, adoption is checked by cautious regional regimes and path-dependent routines (21,30). In the field of materials innovation, adoption depends on a "measurable change" in the parameters of the final product (lifespan, weight, energy efficiency) or on compliance with regulations which reduces uncertainty and increases PU (3,17). Perceived risks – including environmental, health, and safety (EHS) concerns – can outweigh perceived benefits and impede adoption; their salience varies by application domain (18).

3.2 Perceived ease of use (PEOU)

– the degree to which an individual believes that using the system would be free of effort; in firm contexts, this typically entails clarity, process fit, and manageability with available resources (14). Under the OIRs conditions, perceived ease of use (PEOU) increases when the organizational climate is favourable (e.g., group support, readiness for change) – PEOU then increases perceived usefulness (PU) (19). Regional enabling conditions (human capital, R&D spending, entrepreneurship) may indirectly facilitate the introduction of new technologies, although Capello & Lenzi (2021) analyse the emergence rather than the adoption of technologies by firms. Standards and metrology (especially ISO and harmonized testing methods) together with robust testing – e.g., particle release verification – make nano-solutions more "readable" for engineers and EHS professionals, reducing regulatory uncertainty and thereby increasing perceived ease of use (PEOU) (17). In the UTAUT terminology, PEOU corresponds to the construct of effort expectancy; its effect is further reinforced by facilitating conditions (the existence of organizational and technical infrastructure), as summarized in a review study on UTAUT (16); see also (31).

3.3 Attitude / Behavioural Intention (BI)

The approach is an overall assessment of technology use (often omitted in newer versions of TAM, with a direct path from PU to BI). BI is the intention to use or implement technology. At the company level, it is useful to distinguish between BI management (investing, implementing) and BI users (operational use) (15,19). For companies in the OIRs, BI is sensitive to social influences such as pressure from against lead-customers, key customers, and regulatory authorities. Another influence is the perception of risks (EHS, reputation) – both of these factors can slow down the transformation of high PU into realized BI (16,18).

Proximity and network embeddedness – particularly ties to universities, application centres, and lead firms – facilitate collaboration and knowledge flows, lower uncertainty, and strengthen firms’ behavioural intention to adopt. By contrast, weakly connected (“thin”) regional innovation systems and path-dependent lock-ins tend to dampen adoption (4,30). The difference between management intent and user acceptance is key in OIRs.

Implementation challenges often relate to user acceptance, where perceived ease of use (PEOU) is shaped by the work environment, support from superiors, and attitudes toward change. Increasing it requires aligning incentives, targeted training, and clear communication of benefits (19). Success also depends on organizational readiness –especially visible support from top management and the role of "champions" – while their absence is a common inhibitor of adoption (11).

At the individual level in the firm, TAM/UTAUT models explain the perceptual component of acceptance (usefulness/effort, social influence, facilitating conditions, and moderators such as age–gender–experience) (16,32,33). The TOE framework adds the organizational and environmental scaffolding: e.g., top-management support and resources (O), regulatory pressure or partner readiness (E) create a “bridge” between individual willingness and actual adoption.

Case studies show that combining the TAM and TOE models is effective for examining technology adoption precisely in these settings. For example, the study by Lee et al. (19) applied an extended TAM to investigate technology acceptance in IT firms. The sample consisted of 236 South Korean expatriates working in four organizations located in the United States, to identify how perceived benefits and organizational conditions influence decisions to invest in IT. Bryan and Zuva (2021) (12) summarize that the TAM and TOE models are commonly combined in empirical studies analyzing the introduction of new technologies in firms – precisely because of their ability to capture both individual attitudes and system-level determinants. Bryan and Zuva (2021) (12) also propose their integration as one of the most promising approaches for studying technology acceptance, particularly in developing or structurally weaker regions.

The conceptual model of this study posits that the TOE factors influence the core variables of the TAM framework (PE, EE, SI, FC, INN), thereby explaining adoption intention. In particular, the path dependency and network constraints of OIRs are operationalized as sub-dimensions of FC, and together with SI, they are interpreted as mediating and moderating the effects of PE and EE.

4. DISCUSSION AND CONCLUSIONS

This research underscores that the technological attributes of nano-solutions are central to adoption decisions. Firms are more likely to adopt technologies that demonstrate clear and measurable benefits – such as enhanced performance, efficiency, or regulatory compliance – and that align with existing processes and equipment. Technology maturity and the availability of recognized standards and regulatory frameworks further mitigate adoption risks. Nevertheless, EHS concerns remain a critical barrier, particularly in sensitive industries like food and health, where they can outweigh perceived usefulness.

Successful adoption is also contingent on organizational capacity. Firms with slack resources, strong managerial support, and a risk-tolerant culture are better positioned to integrate NaAM. Absorptive capacity – including skilled staff, internal R&D, and established partnerships with knowledge institutions – plays a pivotal role. The presence of internal champions who bridge R&D, quality, and production functions is essential for transitioning projects from prototypes to full-scale implementation.

At the environmental level, strong market demand and clear regulatory enforcement act as powerful incentives. Proximity to universities, testing facilities, and anchor firms lowers transaction costs and accelerates knowledge flows, whereas weak local markets or limited policy support hinder adoption.

The framework also incorporates behavioural insights from the TAM, emphasizing that adoption ultimately depends on PU and PEOU. These perceptions are shaped by the organizational and environmental factors noted above. High PU and PEOU significantly strengthen adoption intentions. However, interactions among these factors are decisive: for instance, even highly promising technologies may be rejected if EHS risks are insufficiently addressed, underscoring the need for robust metrology and certification systems. Similarly, in sectors reliant on legacy equipment, PEOU becomes critical, highlighting the importance of modular deployment and on-site pilots. Internal capacity is equally vital in converting external advantages, such as access to innovation networks, into concrete outcomes; without champions and cross-functional teams, such advantages rarely materialize.

Taken together, these findings demonstrate that adoption emerges not from isolated drivers but from the interplay of technological, organizational, and environmental conditions, reinforced by behavioural perceptions. Effective adoption therefore, requires coordinated alignment across all layers of the TOE+TAM framework. This complexity be illustrated, for example, by the case of Korean old industrial regions (34,35). Pohang and Ulsan, showing how anchor firms and regulatory frameworks shape transitions from legacy industries like steel and petrochemicals toward emerging sectors such as batteries and hydrogen. Yet, shipbuilding hubs like Geoje and Mokpo reveal persistent barriers in testing and certification, underscoring the centrality of FC. At the same time, the transformation of cities such as Suwon, Daejeon, Gwangju, and Pohang into digital clusters demonstrates how strong networks and internal champions can overcome path dependency, echoing the TOE–TAM dynamics highlighted in this study (36).

Future research should investigate how these dynamics vary across industries and regions – for example, between highly regulated sectors like medicine and less regulated ones such as electronics. Longitudinal tracking of objective performance indicators (e.g., yield, energy efficiency, defect rates, compliance times) and assessment of policy experiments, including targeted procurement and testing voucher schemes, would provide stronger evidence of causal mechanisms. Such work is essential to move beyond theoretical frameworks and pilot projects toward sustained, real-world adoption.

To conclude, the adoption of NaAM in OIRs becomes feasible when the promise of PE is effectively translated into the execution of FC. While this study is limited by its reliance on a specific sample and survey-based measures, it offers a conceptual foundation for analyzing adoption in structurally constrained regions and points toward critical avenues for future empirical research.

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ABREVIATIONS

ISO – International Organization for Standardization, REACH – Registration, Evaluation, Authorisation and Restriction of Chemicals, EHS – Environment, Health, and Safety, NaAM – Nanotechnologies and Advanced Materials, OIR – Old Industrial Regions, TRL – Technology Readiness Level, MRL – Manufacturing Readiness Level, R&D – Research and Development, TOE – Technology–Organization–Environment framework, TAM – Technology Acceptance Model, UTAUT – Unified Theory of Acceptance and Use of Technology, PU – Perceived Usefulness, PEOU – Perceived Ease of Use, BI – Behavioral Intention, USE – Use (actual system use), FC – Facilitating Conditions, PE – Performance Expectancy, EE – Effort Expectancy, SI – Social Influence, INN – Innovativeness, IP – Intellectual Property