Journal of Industrial and Business Economics
https://doi.org/10.1007/s40812-026-00424-0

Industry 4.0 and upgrading in the Italian fashion supply chain: a history-friendly model

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Received: 31 October 2025 / Revised: 24 July 2026 / Accepted: 29 July 2026

Abstract

This paper examines how Industry 4.0 technologies reshape the upgrading opportunities of micro and small enterprises (MSEs) in the Italian fashion industry. While digital transformation is widely viewed as a potential source of renewal for mature manufacturing sectors, little is known about whether these technologies generate genuine windows of opportunity for small firms embedded in historically specialized, district-based production systems. Building on the windows of opportunity framework, the paper develops a history-friendly model (HFM) that reproduces key empirical features of the Italian fashion value chain and simulates alternative technological trajectories. The model incorporates heterogeneous suppliers and clients, spatial constraints, capability accumulation, and differentiated Industry 4.0 shocks. Results show that upgrading in the baseline scenario is shaped primarily by geography and access to non-local or multinational clients. Production-Efficiency Enhancers (e.g., robotics, IoT monitoring) do not expand overall upgrading but disproportionately benefit geographically constrained firms by reducing cost disadvantages. In contrast, Capability-Building Technologies (e.g., digital prototyping, additive manufacturing) reduce upgrading opportunities by enabling client firms to internalize functions, despite raising suppliers' learning capacity. These findings highlight the asymmetric and technology-specific nature of digital transformation and call for differentiated industrial policies that consider both spatial inequalities and supply-chain power dynamics.

Keywords Industry 4.0 · Windows of opportunity · History-friendly models · Upgrading · Fashion industry

JEL Codes C63 Computational Techniques · Simulation Modeling · F23 Multinational Firms · International Business · O33 Technological Change · Choices and Consequences · Diffusion Processes

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Published online: 01 September 2026

1 Introduction

The emergence of Industry 4.0 is a central element of current academic and policy debates on how digital and automation technologies reshape competitive dynamics, global value chains (GVCs), and firms' upgrading opportunities (Strange & Zucchella, 2017). While the literature has extensively examined digitalization in large firms and technologically advanced manufacturing sectors (Lee et al., 2023), much less attention has been paid to how micro and small enterprises (MSEs) in traditionally craft-based industries respond to Industry 4.0 and whether these technologies create genuine windows of opportunity for upgrading, i.e. the process by which firms move from low-value to higher-value activities to increase their competitiveness. Understanding how these technologies influence the upgrading trajectories of these firms is crucial not only for assessing their competitiveness but also for evaluating the future of district-based manufacturing in high-income countries.

The Italian fashion industry, including apparel and footwear, offers a valuable context for this analysis, since it represents a paradigmatic example of production systems dominated by small firms, embedded in industrial districts, and shaped by deep historical specialization (Canello, 2022). Fashion has long been characterized by flexible specialization, dense inter-firm networks, and craftsmanship-based production models. These characteristics have historically allowed Italian MSEs to succeed, by serving both domestic lead firms and global luxury brands, providing high-quality production capabilities that are difficult to replicate elsewhere (Berra et al., 1995; Dunford, 2006). However, from the 1990s onward, globalization and the rise of international outsourcing profoundly altered the competitive landscape. Many lead firms increasingly offshored labour-intensive stages of production to lower-cost regions, causing a fragmentation of domestic supply chains and imposing severe pressures on small subcontractors. While some MSEs adapted by specializing further, upgrading their quality, or integrating more closely with lead firms, many others faced decline, exit, or marginalization (Canello et al., 2025). More recently, reshoring and re-localization dynamics have gained visibility, but evidence shows that these processes are often reactive and not necessarily associated with long-term technological upgrading (Buciuni et al., 2022). In this context, the advent of Industry 4.0 appears as a new technological discontinuity that might redefine the relative advantages of domestic versus offshore production, reshape demand for small-firm capabilities, and open new upgrading opportunities.

The concept of windows of opportunity provides a useful theoretical lens to examine these transformations (Perez & Soete, 1988). According to Lee and Malerba (2017), windows of opportunity arise when technological, demand, or institutional shifts temporarily weaken incumbents' advantages and enable new actors to catch up or upgrade. Technological windows are particularly relevant to the current phase of digital transformation: the emergence of cyber-physical systems, robotics, additive manufacturing, or IoT may disrupt existing production architectures, weaken the value of certain routines, and strengthen others, creating possibilities for challengers and agile firms. However, the opening of a technological window does not automatically translate into upgrading; outcomes depend on the firms' strategic response, capability base, and the surrounding institutional and market environments (Hansen & Hansen, 2020). This perspective is especially pertinent for MSEs in advanced economies, which often lack the financial, organisational, or digital capabilities required for adopting complex technologies but may still be able to seize opportunities if technologies align with their existing knowledge base or if they enable new forms of coordination with clients.

The fashion industry presents a paradox in this regard. On the one hand, its intrinsic complexity, linked to fabric pliability, the craft-intensive nature of sewing and assembly, and the importance of tacit knowledge, limits the extent to which automation can substitute labour. Unlike industries such as automotive or electronics, complete automation remains technologically challenging (Fana et al., 2024). On the other hand, several Industry 4.0 technologies can strongly influence upstream production phases, especially cutting, prototyping, modelling, design, quality control, and supply-chain coordination. Tools such as digital prototyping, 3D simulation, additive manufacturing, IoT-based monitoring, and collaborative robots can reduce lead times, improve quality, and enhance integration with lead firms. These technologies may therefore generate new forms of functional upgrading, which refers more specifically to the acquisition of new, higher-value functions within the value chain, such as shifting from manufacturing to design, branding, or marketing (Giuliani et al., 2005; Hernandez-Rodriguez et al., 2025).

Despite the growing policy attention and the expanding empirical literature on digital transformation, it remains unclear which specific Industry 4.0 technologies matter for MSEs in fashion, how they change the distribution of upgrading outcomes across heterogeneous firms, and whether they mitigate or exacerbate long-standing disadvantages arising from geographical constraints, limited absorptive capacity, or dependence on lead firms. Furthermore, because fashion supply chains are interdependent systems, the adoption of Industry 4.0 by clients, such as multinational enterprises (MNEs) or national brands, might reduce the demand for certain supplier functions or reconfigure the boundaries of internalization versus outsourcing, thus indirectly shaping upgrading dynamics for MSEs.

To address these questions, we develop a history-friendly model (HFM) of the Italian fashion industry, grounded in the empirical and theoretical dynamics that characterize the sector. HFMs provide a powerful methodological tool for analysing how technological discontinuities and heterogeneous firm strategies shape long-term evolutionary outcomes (Malerba et al., 2016). By building on appreciative theory and detailed historical reconstruction, HFMs allow scholars to simulate alternative industry trajectories, examine counterfactual scenarios, and assess whether specific mechanisms are capable of reproducing stylized facts. In this study, the model represents the interaction between client firms (MNEs and national clients) and small suppliers in different regions, capturing heterogeneity in capabilities, learning processes, spatial constraints, and technology adoption choices. Beyond the baseline scenario, we introduce two distinct types of Industry 4.0 technologies into the model. The first group (Production-Efficiency Enhancers) includes automation and digital tools that reduce production costs for adopters. The second group (Capability-Building Technologies) includes digital prototyping, AI-assisted design, and additive manufacturing, which increase firms' learning capacity but may also reduce external demand if clients internalize certain functions.

The simulation results show that the emergence of Industry 4.0 does not uniformly translate into new upgrading opportunities for small firms. In the baseline scenario, upgrading is strongly shaped by access to demand, with non-local firms benefiting from broader market linkages, while local firms rely more heavily on connections with multinational clients. The introduction of production-efficiency enhancing technologies does not significantly alter the overall distribution of upgrading outcomes, but it partially compensates for geographical constraints by enabling local firms to improve their competitiveness. By contrast, capability-building technologies generate more ambivalent effects: while they improve learning processes, they also reduce external demand by allowing the internalization of functions by client firms, ultimately leading to fewer upgrading events on average. Overall, the results suggest that the upgrading impact of Industry 4.0 technologies depends critically on how they reshape demand conditions and value-chain organisation, rather than on their direct effects on firm capabilities alone.

Overall, this study provides a threefold contribution. First, it extends the windows of opportunity framework to understand how technological change affects firms operating within mature industrial districts in advanced economies. Second, it adds to the literature on Industry 4.0 adoption among MSEs by distinguishing technologies that enhance process efficiency from those that reshape capability accumulation and outsourcing decisions. Finally, it contributes methodologically by applying a history-friendly modelling approach to a labour-intensive, craft-based industry in which technological disruption unfolds unevenly across functions, providing implications for industrial policy, regional development strategies, and the future of Italy's fashion manufacturing system.

The paper is organised as follows. The next section illustrates the theoretical framework of windows of opportunity. Then we provide a description of the Italian fashion industry, highlighting the role of global value chains and Industry 4.0 technologies. In the following sections we briefly present the methodology and the model. In Sect. 6 we present the results of the simulation exercises. Then we conclude by highlighting the contribution of this paper, as well as its limitations.

2 Windows of opportunity and the Industry 4.0 technological paradigm

The concept of windows of opportunity provides an influential theoretical lens for explaining episodes of industrial upgrading, catch-up, and shifts in competitive leadership. Originally formulated by Perez and Soete (1988), the argument emphasizes that major technological shifts, and in particular the emergence of new techno-economic paradigms, temporarily "level the playing field" by weakening the advantages of incumbents whose capabilities are strongly aligned to the old technological regime. During such periods, technological change may destroy or radically reshape the value of accumulated knowledge, routines, and complementary assets, thus allowing latecomers or smaller firms to reduce competitive gaps with technologically advanced actors. This dynamic is central to understanding how firms, whether in latecomer countries or peripheral positions within advanced economies, can upgrade during periods of discontinuity.

Building on this foundation, Lee and Malerba (2017) significantly expanded the concept of windows of opportunity within the sectoral systems of innovation framework (Malerba, 2002). They proposed that catching-up depends on the interaction between three types of windows of opportunity: technological, demand, and institutional. Although these dimensions often overlap in practice, they represent analytically distinct sources of discontinuity. For the purposes of this study, which examines the strategic responses of small fashion firms to Industry 4.0 technologies, the most relevant dimension is the technological window, which emerges when radical innovations or changes in technological regimes appear. Technological windows arise when new technologies disrupt an industry's existing knowledge base, product architecture, or production processes. Such disruptions often take the form of technological discontinuities, i.e. radical innovations that replace or substantially alter previous technological trajectories and destroy the incumbents' competences (Tushman & Anderson, 1986).

Consistent empirical evidence shows that technological windows can significantly alter market leadership. For example, technological shifts have enabled challengers to catch up in industries such as mobile phones (Giachetti & Marchi, 2017), nuclear power plants (Kwak & Yoon, 2020), cameras (Kang & Song, 2017), regional jets (Vértesy, 2017), and steel (Lee & Ki, 2017). The central mechanism is that incumbents, often locked into existing technologies and exhibiting strong strategic commitments to legacy assets, tend to display inertia in responding to new technological trajectories. They may fall victim to "competency traps", investing further in familiar technologies rather than in uncertain alternatives. As a result, during periods of technological upheaval, "everybody is a beginner" (Park & Lee, 2006), and therefore a temporary advantage is created for challengers willing and able to invest early in the new paradigm.

This logic applies equally to cross-country, inter-firm, and intra-industry catch-up dynamics. Giachetti and Mensah (2023) show that technological windows can reshape the competitive landscape even within the same industry across different product categories. Similarly, Dai et al. (2020) emphasize that profound technological shifts can bring incumbents and latecomers to "the same starting line," providing an opening for rapid capability building. In all cases, technological windows are characterized by temporality: they open when the discontinuity emerges and close once the new technology stabilizes and incumbents reconfigure their capabilities. This temporality underscores why timely strategic responses are crucial.

Although the focus here is on technological windows, it is useful to briefly position them within the broader windows of opportunity framework. Demand windows arise when market demand expands, shifts abruptly, or emerges in previously absent segments. Institutional windows emerge when policy interventions, regulatory changes, or shifts in public incentives reshape industry conditions. Recent work has highlighted the growing relevance of "green" windows of opportunity in environmental sectors, which tend to be strongly driven by policy directionality, institutional change as well as changes in demand (Lema et al., 2020; Hansen & Hansen, 2020). More importantly, technological, demand, and institutional windows often interact.

For example, policy changes encouraging digitalization can accelerate the opening of technological windows by inducing firms to adopt advanced technologies earlier. This interaction is particularly relevant for Industry 4.0 technologies because they are frequently supported by national and regional digitalization policies, incentives for automation, and initiatives promoting supply-chain transparency, sustainability, and traceability. This means that windows of opportunity can be shaped endogenously by the strategic responses of local firms, governments, or other system actors. Yap and Truffer (2019) emphasize the importance of "endogenising" windows through the creation and strengthening of innovation system functions, which allow domestic firms to actively shape selection environments rather than passively respond to global shocks. This endogenous dimension is particularly relevant for small firms in advanced economies: even if major technological shifts originate outside their sector, firms can develop internal capabilities, such as digital skills, experimentation routines, and partnerships, that enable them to leverage these windows more effectively. In this sense, technological windows do not deterministically create upgrading; rather, they create potential for upgrading that must be activated through appropriate strategies (Capone et al., 2021; Davy & Hansen, 2023). So, within this framework, firm strategies play a decisive role in determining whether the potential of a technological window is realized. Lee and Malerba (2017) highlight that windows trigger different responses by incumbents and challengers, which can range from rapid adaptation to rigid adherence to legacy capabilities. Responses include capability reconfiguration, learning strategies, technology adoption choices, and investments in complementary assets such as design, marketing, or supply-chain management.

In summary, the literature shows that technological windows of opportunity do not automatically generate catch-up or upgrading. Their effects depend on firms' existing capabilities, strategic responses, and ability to mobilize complementary assets, as well as on the demand and institutional conditions surrounding technological change. This perspective is particularly relevant to Industry 4.0 in the Italian fashion industry, where new technologies may create opportunities for MSEs, but may also reinforce existing disadvantages if firms lack the capabilities, market access, or value-chain position required to exploit them.

3 Micro and small firms in the Italian fashion industry and the emerging role of Industry 4.0 technologies

3.1 The evolution of the Italian fashion industry

The Italian fashion industry, encompassing apparel, clothing, and footwear, has long been characterized by a dense network of micro and small enterprises (MSEs), many embedded in industrial districts (Berra et al., 1995; Dunford, 2006). As in many Italian districts, these firms historically leveraged craftsmanship, production flexibility, and close inter-firm relationships to compete in global markets (Capasso et al., 2013). These districts have been described as Marshallian socio-economic systems where proximity fosters innovation, knowledge diffusion, and organisational flexibility (Becattini, 1990; Bellandi, 2011). Industrial districts specialize in various stages of production, allowing MSEs to benefit from external economies of scale and low transaction costs (Schamp, 2005; Scott, 2006). Within the value chain, micro and small producers typically occupy specialized upstream and midstream roles, including prototyping, modelling, cutting, weaving, stitching, or finishing. Their centrality in local production systems lies in their ability to support process-embedded innovation, i.e. incremental improvements in materials, processes, and product development that occur throughout the value chain. So, innovation in clothing and footwear tended to emerge within production activities themselves, making small firms indispensable to the innovation strategies of both Italian leading firms and to MNEs (Buciuni et al., 2022).

Over the past three decades, however, the sector has confronted intense pressures from globalization, competitive restructuring, and new technological paradigms (Caniato et al., 2015; Dunford et al., 2016). More specifically, from the 1990s onward, the fashion industry experienced major restructuring due to China's entry into the WTO and the rise of global value chains (Canello et al., 2025). These developments prompted large fashion firms to engage in global sourcing, especially through offshore outsourcing to East Asia and Eastern Europe (Cutrini, 2011; Abernathy et al., 2006). Many Italian MSEs also engaged in offshore outsourcing, but these firms generally maintained domestic subcontracting relationships even when outsourcing abroad, underscoring the enduring role of local production networks (Canello, 2022). Over time, however, globalization also generated severe negative pressures. Declining demand, competitive price pressures, and supply chain restructuring led to widespread firm failures, particularly after the 2008 crisis. Only a small number of firms successfully integrated into GVCs, and those that had adopted in a timely manner strategies involving higher outsourcing propensities and stronger investments in innovation-supporting activities, including technological improvements (Buciuni et al., 2022). This dynamics also affected industrial districts, that experienced significant decline as global competition intensified. For example, in the Prato textile district, between 2001 and 2011 around half of all firms disappeared. Decline was exacerbated by offshoring of key manufacturing phases, rising imports of semi-finished products, entry of low-cost producers (often immigrant-run firms), as well as ageing of skilled workers without sufficient generational renewal (Bressanelli et al., 2022).

While offshoring dominated in the early 2000s, a growing counter-trend of reshoring emerged, motivated both by rising offshore costs and by strategic reconsiderations. In the Italian clothing and footwear sectors, reshoring has been particularly visible among MSEs (Canello, 2022). However, reshoring rarely reflected strong innovation or upgrading strategies, but rather a reactive correction to earlier misjudgments (Canello et al., 2025). So, reshoring MSEs frequently underperformed relative to those that remained offshore, whereas their outcomes improved significantly when reshoring targeted areas with dense subcontracting networks that provided access to competencies and complementary assets that reduced adaptation costs.

3.2 The technological foundations of Industry 4.0 and its role in the reconfiguration of GVCs

These structural changes increased the urgency for technological renewal. In this context, Industry 4.0 technologies represented a key factor in reshaping the upgrading possibilities available to small firms. Indeed, Industry 4.0 can be defined as a major transformation in the organisation of production systems, driven by a set of enabling technologies, such as industrial robotics, additive manufacturing (AM), advanced material handling systems, digital sensors, augmented reality, and the Internet of Things (IoT), that integrate physical and digital processes and enable new forms of data-intensive, automated, and interconnected manufacturing (Martinelli et al., 2021). Industry 4.0 technologies share several common features: integration of cyber-physical systems, automated data collection and analysis, interconnected machines and production cells, and new forms of digitally enabled production flexibility. These technologies emerge at the intersection of multiple technological paradigms, combining mechanical engineering, ICT, AI, and materials science. A key characteristic is their strong complementarity with human capital and organisational capabilities. The digital transition requires new skills in data management, programming, and system integration, as emphasized by multiple studies analysing the labour and skill implications of digital adoption (Cirillo et al., 2023; Ciarli et al., 2021). Firms also need appropriate absorptive capacity to integrate I4.0 technologies effectively (Arcidiacono et al., 2022), a concern that is particularly salient for MSEs with limited managerial and financial resources.

The emerging literature on Industry 4.0 has highlighted that these technologies are altering the logic of international production. Digitalization challenges the traditional cost-based logic that drove the offshoring waves of the 1990s and early 2000s, by reducing the relative importance of low-cost labour and increasing the importance of knowledge, flexibility, and speed (Strange & Zucchella, 2017). More specifically, technologies such as 3D printing or additive manufacturing can shift competitive advantages away from low-cost production locations, by reducing the minimum efficient scale and enabling more localized, customized production (Laplume et al., 2016). These perspectives are consistent with the broader discussion on the future of manufacturing, suggesting that automation and digitalization reduce the opportunities for catching-up by leveraging cheap labour as a source of advantage (Hallward-Driemeier & Nayyar, 2017). Lamperti et al. (2025) show that specific Industry 4.0 technologies have heterogeneous effects on reshoring: countries with higher adoption of advanced industrial robots exhibit greater reshoring from abroad, particularly from Asia; by contrast, IoT investments, used for real-time monitoring, traceability, inventory management, and logistics optimization, are associated with reduced reshoring, likely due to their role in coordinating geographically fragmented supply chains. Finally, additive manufacturing has negligible effects on reshoring at the country level. These results demonstrate that the relationship between digital technologies and GVC restructuring is not linear or uniform. Rather, each technology affects production costs, coordination needs, and scale economies differently. Moreover, the result on robots suggests that automation may mitigate the advantages previously offered by low-wage locations: advanced robotics reduces labour requirements in production tasks and changes the cost structure of manufacturing, potentially reducing the incentives to offshore (Krenz et al., 2021). So, where automation replaces labour-intensive processes, high-income economies may regain competitiveness, altering the geography of global sourcing (Castellani et al., 2022; Chen & Frey, 2024).

Cucculelli et al. (2025) showed that in Italian firms the adoption of these technologies spans a wide range of domains, including interconnected production systems, management software, wearable devices, and augmented reality. Their results indicate an expansion of adoption even among small firms, with significant increases between 2019 and 2022 across technologies that support monitoring, coordination, and process integration. Across sectors, these technologies are reshaping competitive dynamics, firm organisation, and the geography of global production. Their implications are particularly relevant for industries characterized by global fragmentation of production. At the same time, the fragmentation of the supply chain and the erosion of shared know-how represent obstacles to the coordinated technological upgrading needed for Industry 4.0 adoption. The response has partly come through sustainability-driven transformation (Fratocchi & Mayer, 2023), as many circular economy initiatives require traceability systems, digital monitoring, and advanced sorting technologies, suggesting the need for a complementary adoption of digital and sustainable tools (Hervas-Oliver & Capone, 2024).

3.3 The adoption of Industry 4.0 technologies in the fashion industry

The apparel and footwear industries have long been a paradigmatic example of global production fragmentation. They are highly labour-intensive, with significant portions of production having been offshored to low-cost countries. However, they also present specific technological constraints. Although technologies such as automated cutting, vision systems, and digital sensors exist, the pliability and variability of fabrics mean that much of apparel and footwear assembly (especially sewing) remains difficult to automate. This results in a coexistence of new and old production technologies along the supply chain (Fana et al., 2024). Upstream segments (i.e., textiles) and downstream segments (i.e., logistics and retail) exhibit higher levels of automation and digitalization, whereas manufacturing stages involving handling and assembling soft materials remain technologically constrained, limiting the substitution of labour with capital. These characteristics explain why reshoring was relatively limited in fashion manufacturing compared to other manufacturing sectors such as automotive or electronics. Yet, technological upgrading is occurring in specific phases (e.g., pattern making, cutting, prototyping, quality control) and may gradually shift production boundaries. So, while in these industries Industry 4.0 may not lead to complete reshoring, it generates opportunities for functional upgrading, greater integration of design and production processes, and a rebalancing of tasks between domestic and foreign suppliers. Drivers include quality improvement, efficiency, and higher productivity. Skill shortages, especdiially in traditional crafts, also motivate digital upgrading. This dynamics reflect a broader Industry 4.0 pattern: small firms adopt technologies selectively when aligned with perceived bottlenecks or quality needs.

Small fashion firms can leverage Industry 4.0 technologies to support several upgrading trajectories documented in the literature. First, as process innovation is embedded in production activities, these technologies directly reinforce the capabilities that make MSEs competitive, generating process upgrading (Pisano & Shih, 2012). Second, some specific technologies such as 3D modelling, digital prototyping, virtual sampling or simulation tools strengthen the innovation-supporting activities, opening opportunities for functional upgrading (Buciuni et al., 2022). Finally, Industry 4.0 systems enhance integration with lead firms via digital information exchanges (Mejías et al., 2019), that enable relational upgrading. Recent empirical evidence shows that investment has so far focused mainly on implementing technologies aimed at increasing the efficiency of the production process (such as IoT-based monitoring, automation and robotics, and horizontal and vertical coordination systems), since they offer more quantifiable advantages for suppliers in terms of cost reduction and higher knowledge integration (Dal Forno et al., 2023). More limited evidence is instead available about capability-building investments in additive manufacturing and simulation technologies, although the main results suggest that both suppliers and customers might obtain advantages from these technologies (Dal Forno et al., 2023; Celaschi, 2017), and actually could even reduce a firm's dependence on suppliers (Ben-Ner & Siemsen, 2017).

4 Methodology: history-friendly models

To analyse how Industry 4.0 technologies reshape upgrading opportunities for small Italian fashion firms, this study draws on the history-friendly modelling (HFM) methodology. Originally introduced by Malerba et al. (1999), HF models provide a formal, simulation-based framework for explaining the evolution of specific industries through mechanisms that are tightly grounded in empirical evidence and appreciative theorization. The approach has been applied to diverse sectors, including computers, pharmaceuticals, semiconductors, and mobile communications, demonstrating its flexibility in studying how technological and demand shifts shape firm strategies, competitive dynamics, and long-term industry trajectories (Capone et al., 2019; Capone & Li, 2021; Li et al., 2019).

HFMs are rooted in evolutionary economics, and therefore represent firms as heterogeneous, boundedly rational agents whose behaviour is shaped by routines, historically accumulated capabilities, and the institutional and technological environment in which they operate. Firms differ in their innovativeness, knowledge bases, and strategic responses; these differences interact with technological change and demand conditions to generate dynamic industry patterns over time (Nelson & Winter, 1982). HF models adopt this behavioural foundation but add a distinctive emphasis on historical reconstruction, using detailed narratives of how a specific industry evolved to identify the mechanisms that the model must represent (Capone et al., 2019). HF models thus sit between purely verbal appreciative theorizing and highly abstract formal modelling. Appreciative theories, widely used in empirical studies of industrial dynamics, are powerful for identifying causal processes but difficult to test for internal consistency due to their complexity and narrative form. HF methodologies formalize the key mechanisms derived from these appreciative explanations and simulate them to explore their dynamic implications (Capone et al., 2019).

Across applications, HFMs involve three interconnected steps. First, they require the identification of the phenomena to be explained and the mechanisms accounting for them. The starting point is a careful examination of the industry's historical evolution. This involves identifying the salient events, actors, and structural characteristics that shaped the industry trajectory, such as technological discontinuities, entry waves, capability accumulation, or the emergence of segmented markets. For example, in the HF model of mobile communications, Li et al. (2019) identify generational technological change and demand segmentation as key factors enabling the catch-up of Chinese latecomer firms. Similarly, HF models in computers or pharmaceuticals build on historical accounts that highlight the role of technological regimes, appropriability conditions, and strategic behaviour. In our context, this step identifies Industry 4.0 as a major technological discontinuity that alters the competitive environment for small fashion firms, consistent with the windows of opportunity framework detailed in the previous section.

Once the relevant mechanisms are identified, the second step is to build a formal simulation model that captures heterogeneous firms with differentiated capabilities, technological regimes and their evolution (including discontinuities, cumulative learning, and path dependence), demand structures, and institutional elements. HF models retain general evolutionary assumptions but incorporate industry-specific historical features. For instance, in the mobile communications HF model, segmented markets and capability gaps between domestic firms and MNEs play a central role; in the computer industry model, the emergence of new product generations and strong user lock-in are essential mechanisms (Capone et al., 2019; Malerba et al., 2016). In this work, we consider the context of Italian fashion MSEs: technological adoption is shaped not only by digital capabilities but also by the structure of local production networks.

Finally, HFMs are implemented as agent-based simulations, which allow the exploration of dynamic outcomes emerging from firms' interactions and feedback loops. As emphasized by Capone et al. (2019), simulation enables the modeler to test whether a set of mechanisms can reproduce the stylized facts of an industry's evolution and to conduct counterfactual analyses by altering specific parameters or environmental conditions. This counterfactual logic is highly relevant for analysing Industry 4.0 in fashion: by exploring the heterogeneity of Industry 4.0 technological adoption, HFMs can help to identify which technologies create genuine upgrading opportunities for small firms.

5 The model

This section presents an agent-based, history-friendly model of the Italian fashion value chain, designed to examine how Industry 4.0 technologies shape the upgrading trajectories of small supplier firms embedded in global and domestic production networks. The model captures the interaction between two types of actors (client firms and supplier firms) linked through repeated contracting processes for specific value chain functions (e.g., manufacturing, design, prototyping). It combines demand-driven allocation of contracts with endogenous firm learning, capability accumulation, and strategic adaptation. Spatial frictions and differentiated technological shocks are incorporated to simulate the heterogeneous conditions under which Italian micro and small enterprises operate. Figure 1 reports a general overview of the main mechanisms of the model.

5.1 Demand Side: clients, contracts, and bid selection

The model features a fixed population of client firms, divided into Multinational Enterprises (MNEs) and Small National Clients (SNCs). These two groups differ in their scale, quality requirements, and purchasing strategies. MNEs typically demand larger quantities and higher-quality outputs and can allocate a single contract across multiple suppliers. By contrast, SNCs issue smaller contracts, impose lower quality thresholds, and usually rely on suppliers that can fulfill the entire required quantity. In each period, each client issues one or more contracts defined by four attributes: (1) the value-chain function required; (2) the total quantity demanded; (3) the maximum price the client is willing to pay; and (4) the minimum acceptable quality level.

Supplier firms may submit bids to any contract for which they possess the required capability level, provided that the client's maximum price does not fall below the supplier's minimum acceptable price. Firms face a soft production constraint: they may bid on multiple contracts concurrently, but total bid quantities cannot exceed a firm-specific function of production capacity. Geographic constraints are also present: local suppliers may bid only on contracts issued by clients in the same region, whereas non-local suppliers can also access more distant clients. Clients evaluate bids through a weighted scoring rule based on price and expected quality. MNEs assign a higher weight to quality and may accept multiple suppliers to jointly cover demand. SNCs prioritize lower price and award each contract to a single supplier capable of supplying the full quantity. Following selection, suppliers enter a confir-

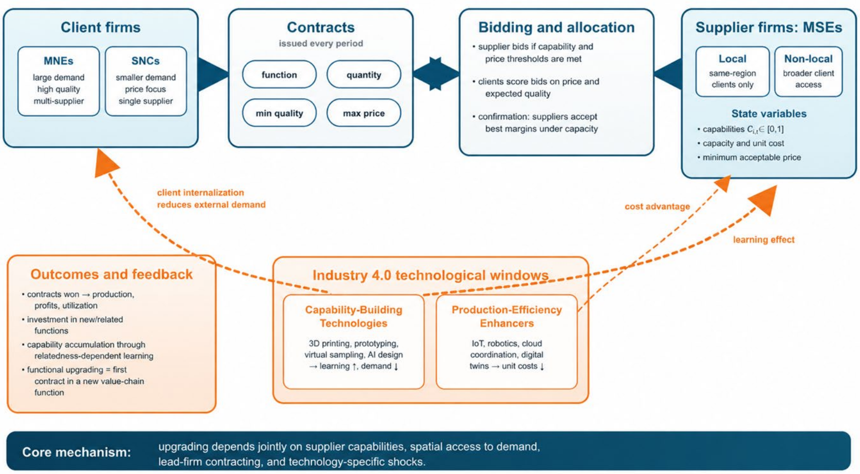

Fig. 1 Overview of the model

mation phase: if assigned more quantity than their capacity allows, they randomly choose some of the contracts and decline the remainder, incurring penalties on unfulfilled commitments.

To capture client learning, contract parameters adapt over time. If a contract is unmet before the confirmation stage, the client relaxes quality requirements. If unmet after confirmation, the client raises the maximum price offered. Conversely, if fully met, clients adjust by modestly tightening requirements: lowering prices and raising minimum quality. Clients thus gradually update their expectations in response to market performance, influencing future competitive dynamics.

5.2 Supply side: capabilities, production, and upgrading

Supplier firms are characterized by a vector of capabilities across all possible value-chain functions. Each capability value lies in the interval [0,1], representing the maximum attainable quality for that function. Firms begin with a fixed specialization: one randomly assigned function receives a higher initial capability value, ensuring initial heterogeneity and comparative advantages. Firms also possess a fixed production capacity, which is not function-specific and constrains the total quantity they can effectively deliver.

Production is modelled in a reduced-form manner. Each unit produced entails a constant unit cost, and profits derive solely from the difference between contract price and cost. Suppliers adjust their minimum acceptable prices based on realized capacity utilization and profitability. If capacity is fully used but desired markups are not met, minimum prices increase. If capacity is underutilized, suppliers reduce minimum prices, potentially even below cost, which can lead to losses but may still be strategically chosen to maintain market presence.

Capability development is a central mechanism in the model. Each period, suppliers decide whether and where to invest in upgrading, based on expected financial gains (drawn from past profitability and market opportunities) and expected technical success (proxied by relatedness to their existing capability base). Capability accumulation follows a relatedness-dependent learning function: capability increments are proportional to both the level of investment and a firm-specific relatedness score, with diminishing returns to effort:

$$C_{i,f}^{t+1} = C_{i,f}^{t} + \eta \cdot \rho_{i,f} \cdot \ln\left(1 + r\pi_{i}^{t}\right) \tag{1}$$

where $C_{i,f}^{t}$ indicates the capabilities of firm i in function f at time t, η is the basic learning rate, $\rho_{i,f}$ is the relatedness score for function f computed from the relatedness matrix of each firm, r is the investment rate, and π_{i}^{t} represents the profit of firm i at time t.

The relatedness matrix is firm-specific and captures how existing competencies facilitate learning in adjacent functions. Upgrading is defined as winning a contract in a function in which the firm had never previously been active, making the acquisition of new functions an observable achievement of capability accumulation.

5.3 Industry structure, entry–exit dynamics, and spatial distribution

The supplier population is initialized using empirical distributions derived from data on the Italian fashion industry (see Canello, 2022, for more information about the data), while the client population is calibrated to maintain aggregate sectoral stability. Firms are assigned to spatial locations following a skewed distribution that mirrors the geographical concentration of Italian textile-fashion districts. Supplier exit occurs when firms accumulate sustained losses or fail to secure contracts for an extended period. For every exit, a new entrant replaces the exiting firm, preserving overall population size. Entrants inherit parameter initialization rules similar to incumbents but reflect updated sectoral conditions, allowing for path-dependent industry dynamics.

5.4 Technological windows of opportunity

Industry 4.0 technologies are introduced as technological windows that change either (1) the efficiency of performing existing functions or (2) firms' ability to learn new functions. Production-Efficiency Enhancers include IoT-based monitoring, robotics, cloud coordination systems, and digital twins. Their effect on efficiency is modelled by a reduction of unit costs for adopter firms. Capability-Building Technologies, such as 3D printing, digital prototyping, virtual sampling, and AI-assisted design, instead directly relax capability barriers. They increase the learning rate for adopters, thereby potentially improving the attainable quality in the selected function and facilitating functional upgrading. However, as they can be also adopted by client firms (Dal Forno et al., 2023; Ben-Ner & Siemsen, 2017), they also generate a reduction in external demand by enabling client firms to internalize production. By introducing these shocks in separate simulation experiments, the model examines how different technological pathways influence the upgrading options available to small suppliers.

6 Results

In this section, we present the results obtained by running computer simulations of our model. First, we run baseline simulations that represent the conditions of the fashion industry before the adoption of Industry 4.0 technologies. Then, we run history-divergent simulations to examine the impact of the adoption of these technologies. More specifically, we focus on two main changes in the sectoral system: the adoption of Production-Efficiency Enhancers and the adoption of Capability-Building Technologies. In both cases, we assume that only a limited fraction of firms (10%) adopt the specific technology. For each of the three cases (the baseline model and the two history-divergent cases) we run 50 simulations. Parameter values and and initial conditions are specified in Table A1 in the Appendix. To check the robustness of our results to small changes in parameter values, we conduct a sensitivity analysis (Landini et al., 2017; Li et al., 2019). Within a range of variation of [-10%, + 10%] of the original parameter values included in Table A1, the results of the model are qualitatively confirmed. The changes in the model to represent the history-divergent cases are described below. In all cases, the main variable of interest is functional upgrading, that is the first entry into a new value-chain function through contract acquisition.

6.1 Baseline model

In the baseline model, only a small fraction of firms never manages to upgrade in at least one function over the 50 periods analysed by each simulation (Fig. 2). The number of upgrading events, however, is not related to the size of the firm (Fig. 3). Figure 4 shows the distribution of upgrading events for local and non-local firms. Local firms can access only clients from the same region in which they are localized; non-local firms, instead, can also access more distant clients. The figure shows in a very clear way that upgrading is much more common in non-local firms, that can exploit demand opportunities that are not limited to their home region. Local firms can partially compensate if they are able to access contracts from MNEs (Fig. 5), that generally pay higher prices, although they have higher quality requirements and are not equally distributed across regions. The ability to gain contracts from MNEs has an effect also on non-local firms, but it is considerably more limited.

6.2 Production-efficiency enhancers

In the first history-divergent exercise, we introduce the possibility for some firms to adopt production-efficiency enhancing technologies. This implies that adopting firms benefit from a lower cost of production (a 20% reduction). In order to isolate

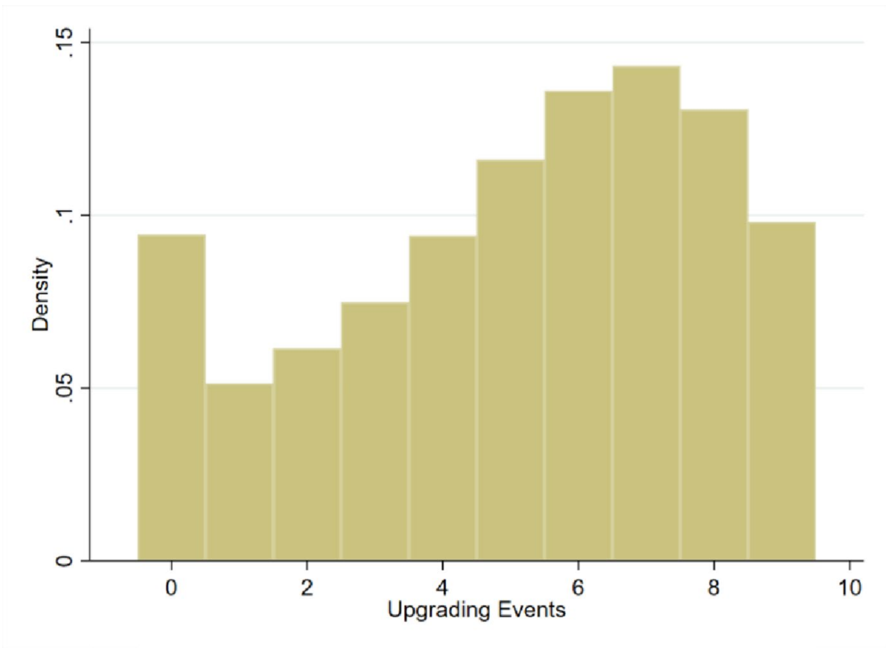

Fig. 2 Baseline Model: Distribution of upgrading events

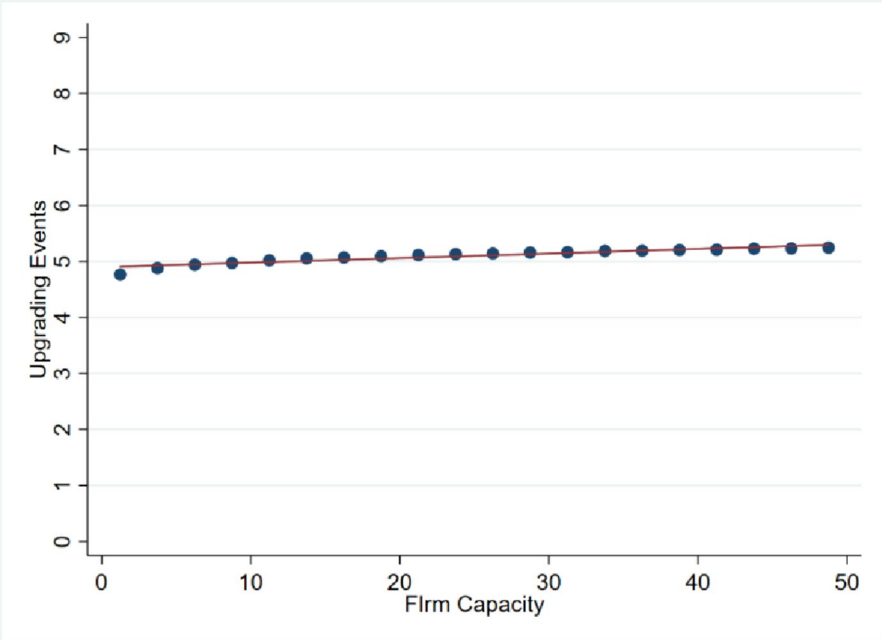

Fig. 3 Baseline Model: Relation between upgrading events and firm capacity

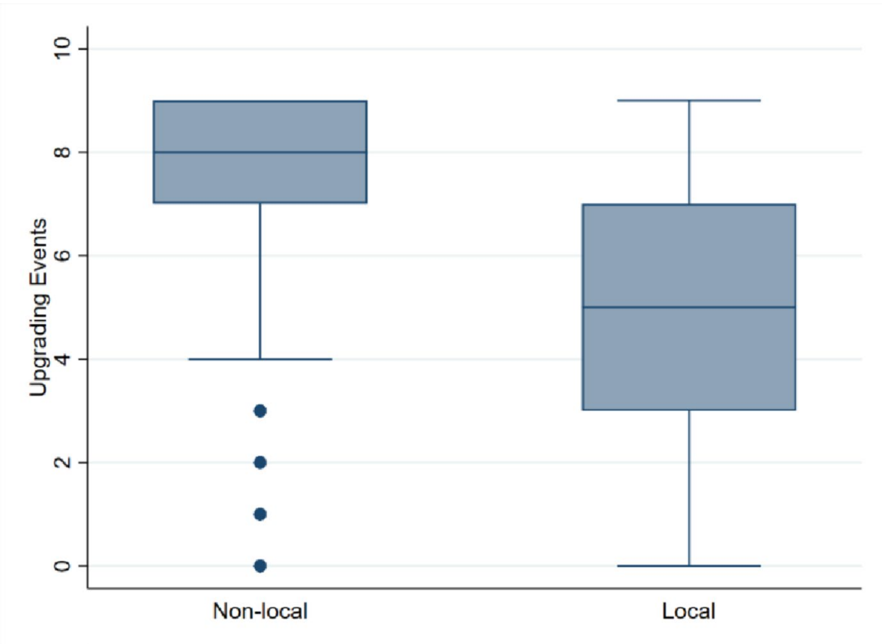

Fig. 4 Baseline Model: Distribution of upgrading events in local and non-local firms

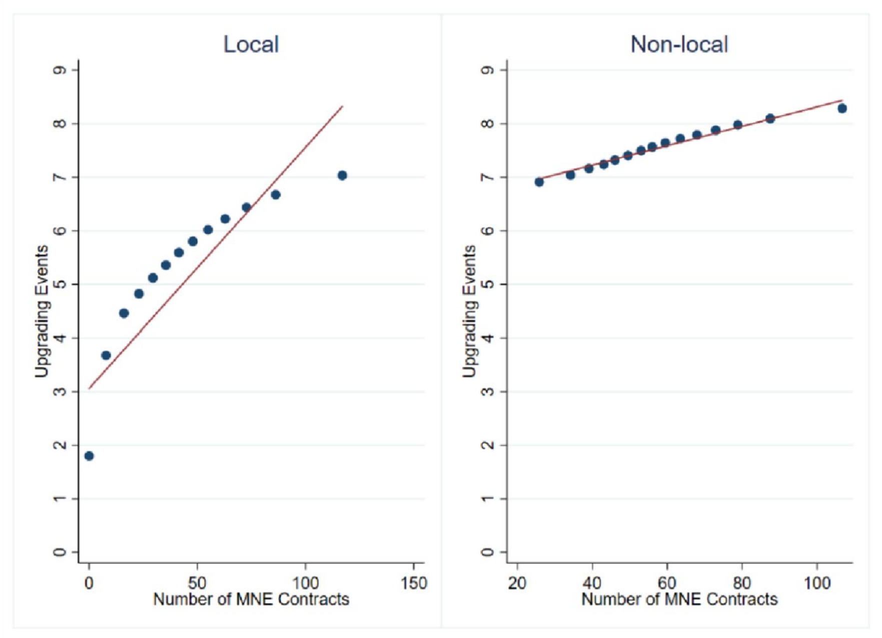

Fig. 5 Baseline Model: Relation between upgrading events and MNEs contracts in local and non-local firms

the effect of technology adoption, we assume that this occurs independently of other relevant factors, such as the local status of firms, as well as the characteristics of the region in which it is localized. Figure 6 shows that the adoption of these technologies has no impact on the distribution of upgrading events. The adoption of efficiency enhancing technologies, however, generates an effect quite similar to the exposure to non-local markets: Fig. 7 shows that the average number of upgrading events is similar among local adopters, non-local non-adopters, and non-local adopters, and is substantially lower for local non-adopters. So, the adoption of these technologies provides upgrading opportunities in particular to local firms, whereas for non-local firms the impact is quite limited, since they could already exploit their linkages outside the home region. This pattern is confirmed by Fig. 8, that shows how the number of contracts gained from MNEs is less important for non-local and/or adopter firms, and instead offers some upgrading opportunity to local non-adopters.

6.3 Capability-building technologies

The second group of Industry 4.0 technologies generates different results. This is quite evident from the distribution of upgrading events, which now has a peak at 0, and a much lower mean (Fig. 9). This probably reflects the reduction in demand associated with the emergence of these technologies, since they allow client firms to perform some functions by themselves. This lack of demand is not compensated by the higher learning rate that allows firms to accumulate capabilities with lower

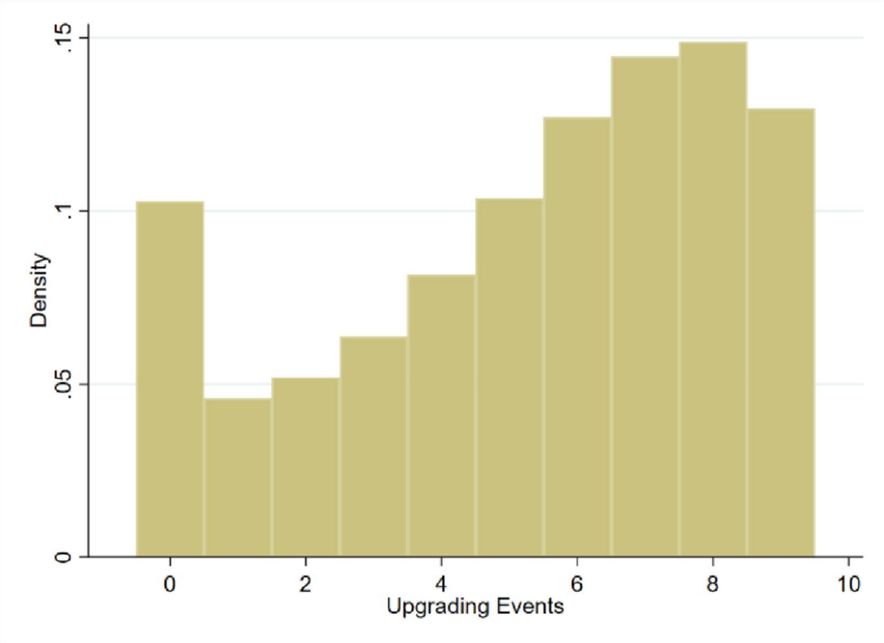

Fig. 6 Production-Efficiency Enhancers: Distribution of upgrading events

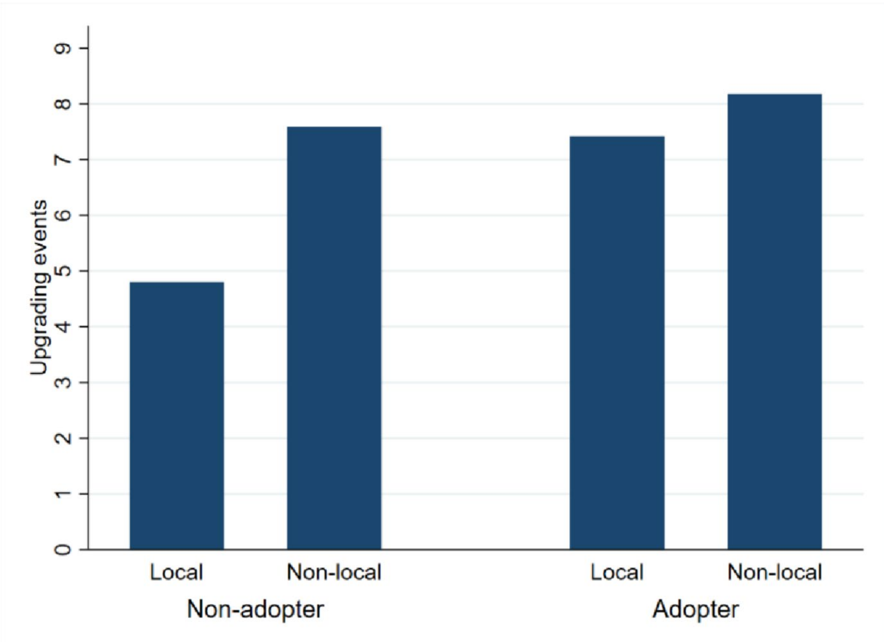

Fig. 7 Production-Efficiency Enhancers: Average number of upgrading events in different types of firms

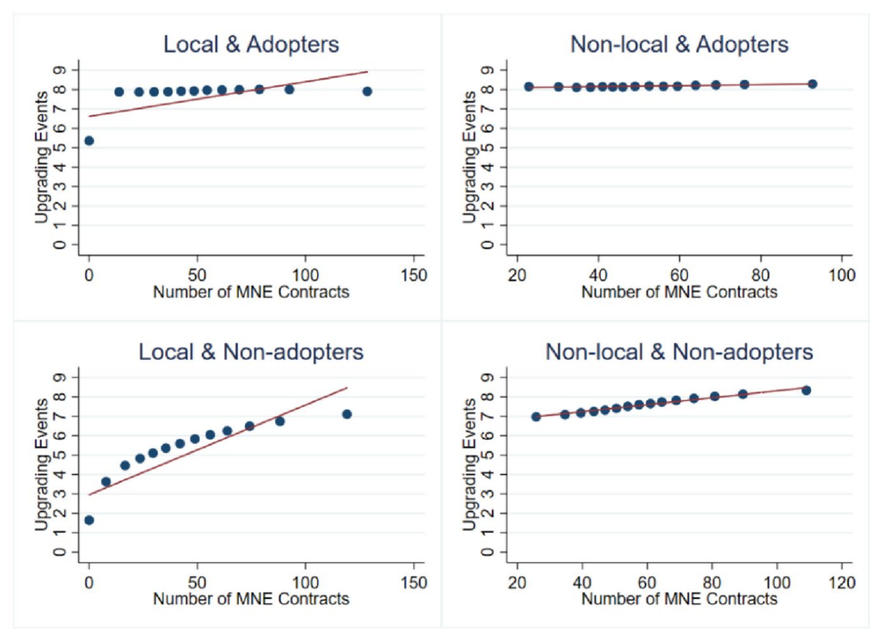

Fig. 8 Production-Efficiency Enhancers: Relation between upgrading events and MNE contracts in different types of firms

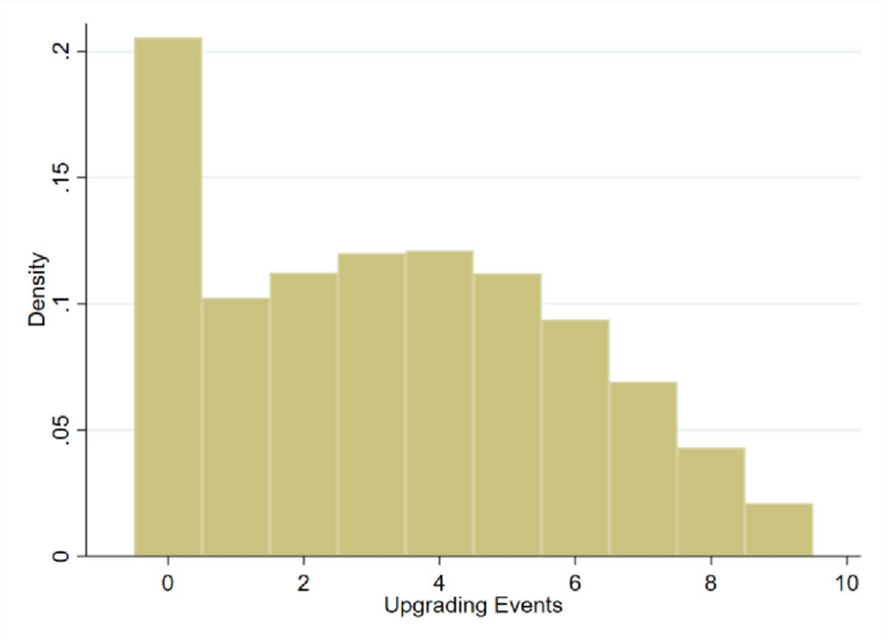

Fig. 9 Capability-Building Technologies: Distribution of upgrading events

effort. Figure 10 shows that these technologies offer only limited opportunities for upgrading, and that actually the impact is slightly stronger for non-local firms. As in the baseline model, access to MNE contracts remains the main upgrading strategy for local firms, whether they are technology adopters or not (Fig. 11).

7 Conclusion

This paper examined how Industry 4.0 technologies shape the upgrading opportunities of micro and small enterprises in the Italian fashion industry, using a history-friendly model that reproduces stylized facts of the sector and simulates alternative technological trajectories. The results shed light on the heterogeneous and technology-specific nature of the digital transformation, showing that not all technologies create windows of opportunity, and that the distribution of benefits is highly uneven across firms. More broadly, the findings highlight the importance of understanding digitalization not as a homogeneous shift but as a collection of distinct technologies with different implications for production costs, learning dynamics, and client-supplier relationships.

The results obtained in the baseline model capture upgrading dynamics in the absence of Industry 4.0 technologies. Even without technological shocks, the model shows that a large share of small firms manages to upgrade at least once. This is consistent with the historically observed fluidity of the Italian fashion supply chain,

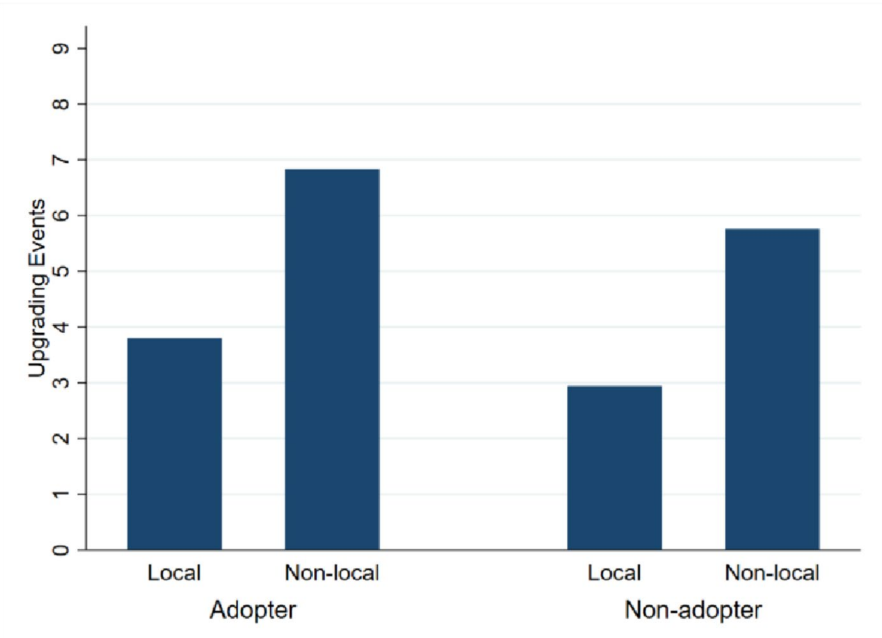

Fig. 10 Capability-Building Technologies: Average number of upgrading events in different types of firms

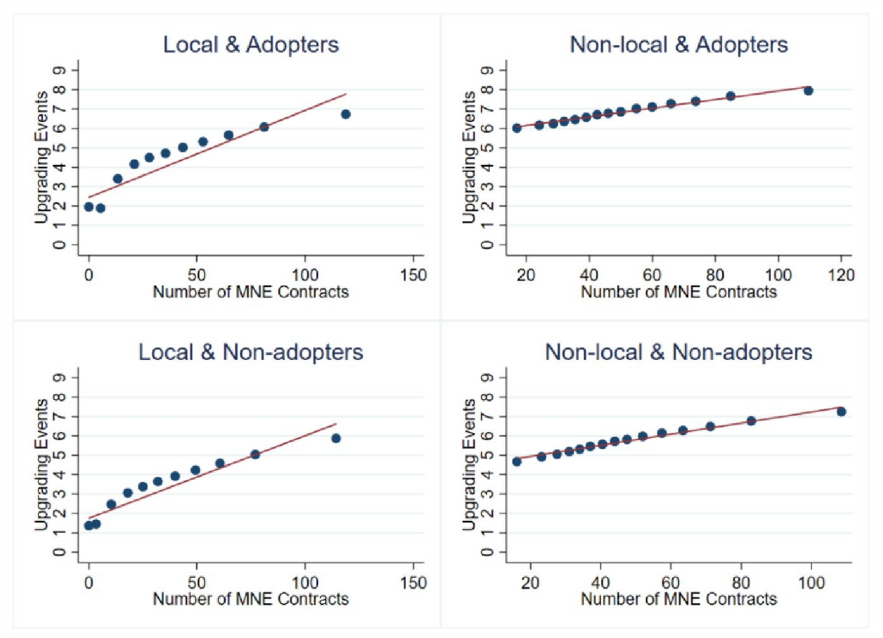

Fig. 11 Capability-Building Technologies: Relation between upgrading events and MNE contracts in different types of firms

that has been characterized by a relational mode of value chain governance in which suppliers are able to work autonomously and enlarge their competences by investing in new functions (De Marchi & Di Maria, 2019). However, upgrading is strongly conditioned by geography and demand structure: firms with access to non-local markets and those able to connect to multinational clients exhibit significantly higher upgrading rates. This finding reinforces well-established empirical evidence on the advantages of external linkages (Giuliani et al., 2005) and the centrality of lead firms in enabling capability development among small suppliers, in line with the historical evolution of the Italian fashion districts and the impact that MNEs' entry had on their upgrading opportunities (Amighini & Rabellotti, 2006; Carmine et al., 2024). Local firms not connected to MNEs are structurally disadvantaged, even when their internal capabilities are sufficient to compete.

When introducing Production-Efficiency Enhancers, the model reveals that cost-reducing technologies do not significantly change the overall distribution of upgrading events but have meaningful redistributive effects. Local firms, traditionally constrained by geographically limited demand, benefit disproportionately from adopting these technologies. By reducing unit costs through the adoption of the new technologies, these firms become more competitive in bidding for contracts, thereby partially compensating for their lack of access to non-local client networks. In contrast, non-local firms, already advantaged by broader demand opportunities, experience only marginal gains from adopting efficiency technologies. These results suggest that cost-reducing I4.0 technologies may act as partial equalizers, reducing regional disadvantages without fundamentally reshaping industry structure. At the same time, the redistributive nature of these technologies underscores a broader point: technologies that primarily improve cost efficiency do not inherently generate new upgrading opportunities, but they strengthen existing competitive logics. They do not alter the capability requirements for performing new functions, nor do they modify the fundamental dependence of MSEs on client-driven demand. Their benefits materialize as they help firms meet existing quality or price thresholds, rather than enabling them to move into new value-chain functions. As such, these technologies support incremental upgrading rather than structural transformation.

The introduction of Capability-Building Technologies tells a different story. These technologies are designed to lower learning barriers and facilitate functional upgrading by enhancing firms' ability to accumulate new competencies. Unexpectedly, however, the results show that they substantially reduce the overall incidence of upgrading. This counterintuitive outcome is explained by their dual effect: while they increase firms' learning capacity, they simultaneously reduce external demand because client firms begin internalizing certain functions. In industries like fashion, where clients have strong incentives to centralize design, prototyping, or simulation activities, the adoption of capability-building technologies by lead firms can shrink the scope of activities that suppliers can perform. As a result, despite their potential to enhance learning, these technologies narrow the windows of opportunity available to suppliers by reducing market access. Indeed, the limited evidence on the implementation of additive manufacturing and simulation technologies shows that they tend to reduce customers' dependence on suppliers (Ben-Ner & Siemsen, 2017; Dal Forno et al., 2023). Moreover, the model shows that the limited upgrading potential that remains under capability-building technologies is slightly skewed toward non-local firms, which can compensate for reduced domestic demand by accessing a broader set of clients. Local suppliers, already marginalized in the baseline scenario, face even stronger disadvantages when client-side technological adoption alters the boundaries of the value chain. This dynamics also point to a broader transformation in the locus and organisation of knowledge within the value chain. When capability-building technologies are also adopted by client firms, the accumulation of knowledge may progressively shift away from suppliers towards vertically integrated actors. In this sense, the reconfiguration of firm boundaries observed in the model can be interpreted not only as a change in the allocation of tasks, but also as a redistribution of knowledge across the industry, with important implications for long-term capability development (Steinmueller, 2006). Moreover, shifts in the distribution of capabilities across upstream and downstream actors can induce processes of integration or disintegration, reshaping market structure and competitive dynamics over time (Malerba et al., 2008; Helfat, 2015). In our context, the internalization of advanced functions by lead firms may therefore not only reduce short-term upgrading opportunities for suppliers, but also generate longer-term risks of capability erosion and deskilling, as suppliers become increasingly specialized in narrower, lower-value tasks. This suggests that technological change may reinforce asymmetries in knowledge and control within value chains, potentially leading to more concentrated and hierarchical industrial structures (Gereffi et al., 2005).

Taken together, these findings highlight the asymmetric nature of technological windows in fashion. Technologies that reduce costs may modestly democratize upgrading opportunities, especially for geographically constrained firms. In contrast, technologies that restructure capability hierarchies may close upgrading opportunities for suppliers by shifting the locus of knowledge creation and production upstream to client firms. The results contribute to the literature on windows of opportunity by showing that technological windows are not uniformly beneficial (Lee & Malerba, 2017; Hansen & Hansen, 2020) and may, under certain conditions, become "windows of vulnerability" for smaller firms. They also refine the understanding of digital transformation in MSEs by emphasizing the importance of distinguishing between technologies that modify production efficiency and those that reshape learning dynamics and power relations in supply chains. The study thus underscores the need for a granular, technology-specific approach to theorizing digitalization.

Our findings have some implications for industrial and regional policy. First, policies promoting Industry 4.0 adoption among MSEs should avoid "one-size-fits-all" approaches. Technologies have different systemic effects: while efficiency technologies can support local upgrading, capability-building technologies may require complementary interventions, such as collaborative platforms, shared prototyping facilities, or incentives for lead firms to outsource advanced functions, to prevent unintended negative consequences. Second, regional development strategies should focus on reducing spatial inequalities in access to demand. The model shows that geography remains a key determinant of upgrading, suggesting that digital infrastructure and mechanisms to connect small suppliers to national and international clients can be powerful complements to technology adoption policies. Third, to prevent the internalization of key functions by lead firms from displacing supplier capabilities, policies could promote open innovation frameworks and encourage lead firms to maintain collaborative value-chain structures. This is particularly relevant in sectors, such as fashion, where craft-based knowledge and embodied skills remain essential. Finally, and more broadly, our findings speak to the renewed debate on industrial policy, suggesting that technological opportunities alone are insufficient to ensure upgrading and must be embedded within a coherent, mission-oriented policy framework. As highlighted in the recent literature (Juhász et al., 2024; Terzi et al., 2023), industrial policy can be understood as a set of selective interventions aimed at directing the structure of production toward activities with higher long-term growth potential, particularly in contexts characterized by strong path dependence, coordination failures, and global competition, such as digital technologies and especially artificial intelligence (Fontana & Vannuccini, 2024). From this perspective, the non-deterministic relationship between technological windows and upgrading identified in this paper reinforces the view that markets alone may not generate desirable structural transformations. Instead, public intervention can play a fundamental coordination role in aligning firm behaviour, technological trajectories, and demand conditions.

This study has several limitations. The model abstracts from firm-level financial constraints, managerial skills, and institutional environments that influence real-world technology adoption. It also assumes limited forms of inter-firm collaboration, whereas empirical evidence shows that learning often occurs through networks, shared suppliers, and district-level institutions. Moreover, the modelling of client internalization is stylized; future models could introduce heterogeneity in client strategies or explore multi-tier supply chains. A notable assumption in the model is the use of a fixed population of supplier firms, which emerges from the mechanism of exit associated with replacement entry, and is motivated by the increased model complexity that an explicit treatment of entry would require (Capone, 2024). Therefore, a natural extension of the model would be to relax this assumption, by explicitly modelling firm entry, exit, and the reallocation of market shares across heterogeneous suppliers. This would make it possible to capture changes in the size distribution of firms and to analyse how upgrading dynamics interact with processes of industrial restructuring. In this respect, empirical cases such as the Prato textile district, could provide an interesting setting, suggesting that structural change may occur not only through net firm exit, but also through compositional shifts within a relatively stable population, for instance via the entry of new Chinese producers alongside the growth of surviving incumbent firms (Dei Ottati, 2009; Lombardi & Sforzi, 2016). Such dynamics are often associated with increasing heterogeneity in firm size and organisational forms, including the coexistence of larger, more integrated firms and smaller, more fragmented production units (Lazzeretti & Capone, 2017). Incorporating these mechanisms into the model would allow future work to explore how technological adoption interacts with demographic and structural transformations of the supplier base, and whether these changes reinforce or hinder upgrading trajectories. Another simplifying assumption concerns the absence of explicit costs associated with the adoption of Industry 4.0 technologies. In the model, technological adoption does not entail short-term financial burdens, such as the acquisition of advanced machinery or digital infrastructure, which in reality may temporarily compress profits and increase exit risks, especially for smaller firms, mirroring an analogous trade-off associated with robot adoption for large firms (Antonioli et al., 2024). As a result, the model does not capture potential "slump–rebound" dynamics, whereby short-term disruption and selection effects are followed by longer-term productivity gains. Introducing such costs, and more generally endogenising technology adoption decisions, would allow future work to investigate the interaction between financial constraints, firm selection, and the diffusion of advanced technologies, as well as their implications for industrial dynamics and upgrading trajectories.

Notwithstanding these limitations and the scope for further extensions, the model provides a coherent explanation of the main mechanisms that have shaped upgrading in the Italian fashion supply chain. By reproducing the interaction between geographical constraints, access to different types of clients, capability accumulation, and technology-specific changes, the analysis offers a robust framework for interpreting both the historical evolution of the sector and the heterogeneous consequences of Industry 4.0 for micro and small suppliers.

Appendix

See Table 1.

Table 1 Parameter values of the baseline model

Parameter	Value
Number of Simulations	50
Number of Periods	50
Number of Regions	500
Maximum Number of Suppliers (per Region)	500
Maximum Number of Clients (per Region)	50
Fraction of Local Firms	0.9
Maximum Capacity of Suppliers	50
Number of Functions	10
Unit Production Cost	10
Target Markup	2
Specialization Capability (Range)	[0.2–0.5]
Other Capabilities (Range)	[0–0.2]
Supplier – Maximum Increase in Price	0.05
Supplier – Maximum Decrease in Price	0.005
Client – Maximum Increase in Quality	0.05
Client – Maximum Increase in Price	0.05
Client – Maximum Decrease in Quality	0.01
Client – Maximum Decrease in Price	0.01
Fraction of MNEs	0.1
Size of MNEs	500
Maximum Size of SNCs	300
Price Weight for MNEs	0.25
Price Weight for SNCs	0.75
Learning Rate	0.01
Investment Rate	0.5
Fraction of Technology Adopters	0.1

Acknowledgments We are grateful to two anonymous reviewers for their insightful and constructive comments, which have significantly improved the manuscript; any remaining errors or shortcomings are our sole responsibility. Jacopo Canello is grateful to the Italian Tax Revenue Agency for providing access to the data used for this research. The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the agency. Due to privacy and confidentiality restrictions, these data cannot be shared or made publicly available.

Funding Open access funding provided by Università degli Studi di Parma within the CRUI-CARE Agreement. The research leading to these results has received funding from the European Research Council under the European Union's Horizon Europe Programme (Grant Agreement No. 101169652 SOS-GVC – ERC-2024-CoG) and from the Italian Ministry of University and Research (MUR) under the PRIN2022 Programme: 2022ACJ2WS - Automation, Trade, and Global Value Chains: New Empirical Evidence and Theory Development, CUP: D53D23006320006. As set out in the Grant Agreement, beneficiaries must ensure that at the latest at the time of publication, open access is provided via a trusted repository to the published version or the final peer-reviewed manuscript accepted for publication under the latest available version of the Creative Commons Attribution International Public License (CC BY) or a license with equivalent rights. CC BY-NC, CC BY-ND, CC BY-NC-ND or equivalent licenses could be applied to long-text formats.

References

Abernathy, F. H., Volpe, A., & Weil, D. (2006). The future of the apparel and textile industries: Prospects and choices for public and private actors. *Environment and Planning A*, *38*(12), 2207–2232.

Amighini, A., & Rabellotti, R. (2006). How do Italian footwear industrial districts face globalization? *European Planning Studies*, *14*(4), 485–502.

Antonioli, D., Marzucchi, A., Rentocchini, F., & Vannuccini, S. (2024). Robot adoption and product innovation. *Research Policy*, *53*(6), 105002. https://doi.org/10.1016/j.respol.2024.105002

Arcidiacono, F., Ancarani, A., Di Mauro, C., & Schupp, F. (2022). The role of absorptive capacity in the adoption of smart manufacturing. *International Journal of Operations & Production Management*, *42*(6), 773–796.

Becattini, G. (1990). The Marshallian industrial district as a socio-economic notion. In F. Pyke, G. Becattini, & W. Sengenberger (Eds.), *Industrial Districts and Interfirm Cooperation in Italy*. International Institute for Labour Studies.

Bellandi, M. (2011). Perspectives on mature marshallian industrial districts. In: Handbook of Regional Innovation and Growth. https://doi.org/10.4337/9780857931504.00016

Ben-Ner, A., & Siemsen, E. (2017). Decentralization and localization of production: The organizational and economic consequences of additive manufacturing (3D printing). *California Management Review*, *59*(2), 5–23.

Berra, L., Piatti, L., & Vitali, G. (1995). The internationalization process in the small and medium sized firms: A case study on the Italian clothing industry. *Small Business Economics*, *7*, 67–75.

Bressanelli, G., Visintin, F., & Saccani, N. (2022). Circular Economy and the evolution of industrial districts: a supply chain perspective. *International Journal of Production Economics*, *243*, 108348.

Buciuni, G., Canello, J., & Gereffi, G. (2022). Microfoundations of global value chain research: Big decisions by small firms. *Environment and Planning A: Economy and Space*, *54*(6), 1086–1111.

Canello, J. (2022). Mimetic isomorphism, offshore outsourcing and backshoring decisions among micro and small enterprises. *Regional Studies*, *56*(5), 719–736.

Canello, J., Landini, F., & Tredicine, L. (2025). Beyond the giants: the hidden role of micro and small enterprises in GVC reconfiguration dynamics. *Journal of International Business Policy*, *8*, 251–269. https://doi.org/10.1057/s42214-025-00218-6

Caniato, F., Crippa, L., Pero, M., Sianesi, A., & Spina, G. (2015). Internationalisation and outsourcing of operations and product development in the fashion industry. *Production Planning & Control*, *26*(9), 706–722.

Capasso, M., Cusmano, L., & Morrison, A. (2013). The determinants of outsourcing and offshoring strategies in industrial districts: Evidence from Italy. *Regional Studies*, *47*(4), 465–479.

Capone, G. (2024). Outside In: Challenges for evolutionary studies on entry. *Industrial and Corporate Change*, *33*(1), 268–276.

Capone, G., & Li, D. (2021). History-Friendly Modeling: An Evolutionary Tool for Strategy Research. *Strategy Science*, *6*(4), 436–443. https://doi.org/10.1287/stsc.2021.0133

Capone, G., Malerba, F., Nelson, R. R., Orsenigo, L., & Winter, S. G. (2019). History-friendly models: Retrospective and future perspectives. *Eurasian Business Review*, *9*(1), 1–23.

Capone, G., Li, D., & Malerba, F. (2021). Catch-up and the entry strategies of latecomers: Chinese firms in the mobile phone sector. *Industrial and Corporate Change*, *30*, 189–213.

Carmine, S., De Marchi, V., & Grandinetti, R. (2024). Industrial districts, multinational corporations, and their local/global paradoxes. *Investigaciones Regionales-Journal of Regional Research*, *60*, 89–103. https://doi.org/10.38191/iirr-jorr.24.025

Castellani, D., Lamperti, F., & Lavoratori, K. (2022). Measuring Adoption of Industry 4.0 Technologies via International Trade Data: Insights from European Countries. *Journal of Industrial and Business Economics* 49 (1): 51–93. https://doi.org/10.1007/s40812-021-00204-y.

Celaschi, F. (2017). Advanced design-driven approaches for an Industry 4.0 framework: The human-centred dimension of the digital industrial revolution. *Strategic design research journal*, *10*(2), 97–104.

Chen, C., & Frey, C. (2024). Robots and Reshoring: A Comparative Study of Automation, Trade, and Employment in Europe. *Industrial and Corporate Change*, *33*(6), 1331–1377. https://doi.org/10.1093/icc/dtae012

Ciarli, T., Kenney, M., Massini, S., & Piscitello, L. (2021). Digital technologies, innovation, and skills: Emerging trajectories and challenges. *Research Policy*, *50*(7), 104289. https://doi.org/10.1016/j.respol.2021.104289

Cirillo, V., Fanti, L., Mina, A., & Ricci, A. (2023). The adoption of digital technologies: Investment, skills, work organisation. *Structural Change and Economic Dynamics*, *66*, 89–105. https://doi.org/10.1016/j.strueco.2023.04.011

Cucculelli, M., Lamperti, F., Mondolo, J., Pompei, F., & Venturini, F. (2025). Firm adoption of Industry 4.0 technologies in times of economic turmoil: the role of enabling factors. *Journal of Technology Transfer*. https://doi.org/10.1007/s10961-025-10263-1

Cutrini, E. (2011). Moving eastwards while remaining embedded: The case of the Marche footwear district, Italy. *European Planning Studies*, *19*(6), 991–1019.

Dai, Y., Haakonsson, S., & Oehler, L. (2020). Catching up through green windows of opportunity in an era of technological transformation: Empirical evidence from the Chinese wind energy sector. *Industrial and Corporate Change*, *29*, 1277–1296.

Dal Forno, A. J., Bataglini, W. V., Steffens, F., & Ulson de Souza, A. A. (2023). Industry 4.0 in textile and apparel sector: a systematic literature review. *Research Journal of Textile and Apparel*, *27*(1), 95–117.

Davy, E., & Hansen, U. E. (2023). A firm-level perspective on windows of opportunity. *Technology in Society*, *75*, 102374.

De Marchi, V., & Di Maria, E. (2019). Environmental upgrading and suppliers' agency in the leather global value chain. *Sustainability*, *11*(23), 6530.

Dei Ottati, G. (2009). An industrial district facing the challenges of globalization: Prato today. *European Planning Studies*, *17*(12), 1817–1835.

Dunford, M. (2006). Industrial districts, magic circles, and the restructuring of the Italian textiles and clothing chain. *Economic Geography*, *82*(1), 27–59.

Dunford, M., Dunford, R., Barbu, M., & Liu, W. (2016). Globalisation, cost competitiveness and international trade: The evolution of the Italian textile and clothing industries and the growth of trade with China. *European Urban and Regional Studies*, *23*(2), 111–135.

Fana, M., Bárcia de Mattos, F., Esquivel, V., Anzolin, G., Kucera, D., & Tejani, S. (2024). *The effects of automation in the apparel and automotive sectors and their gender dimensions*. Publications Office of the European Union. https://doi.org/10.2760/94475

Fontana, O., & Vannuccini, S. (2024). How to Institutionalise European Industrial Policy (for Strategic Autonomy and the Green Transition). *Journal of Industry Competition and Trade*, *24*, 20. https://doi.org/10.1007/s10842-024-00429-2

Fratocchi, L., & Mayer, J. (2023). The impact of environmental and social sustainability on the reshoring decision making and implementation process: insights from the bicycle industry. *Operations Management Research*, *16*(2), 574–593.

Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy*, *12*(1), 78–104.

Giachetti, C., & Marchi, G. (2017). Successive changes in leadership in the worldwide mobile phone industry: the role of windows of opportunity and firms' competitive action. *Research Policy*, *46*, 352–364.

Giachetti, C., & Mensah, D. T. (2023). Catching-up during technological windows of opportunity: An industry product categories perspective. *Research Policy*, *52*(2), 104677.

Giuliani, E., Pietrobelli, C., & Rabellotti, R. (2005). Upgrading in global value chains: lessons from latin american clusters. *World Development*, *33*(4), 549–573.

Hallward-Driemeier, M., & Nayyar, G. (2017). *Trouble in the Making? The Future of Manufacturing-led Development*. World Bank.

Hansen, U. E., & Hansen, S. (2020). How many firms benefit from a window of opportunity? knowledge spillovers, industry characteristics, and catching up in the chinese biomass power plant industry. *Industrial and Corporate Change*, *29*, 1211–1232.

Helfat, C. E. (2015). Vertical firm structure and industry evolution. *Industrial and Corporate Change*, *24*(4), 803–818.

Hernández-Rodríguez, E., Boschma, R., Morrison, A., & Ye, X. (2025). Functional upgrading and downgrading in global value chains: Evidence from EU regions using a relatedness/complexity framework. *Papers in Regional Science*, *104*(1), 100072. https://doi.org/10.1016/j.pirs.2024.100072

Hervas-Oliver, J. L., & Capone, F. (2024). Clusters and industrial districts in the twin transition. *Competitiveness Review*, *34*(5), 857–863. https://doi.org/10.1108/CR-09-2024-313

Juhász, R., Lane, N., & Rodrik, D. (2024). The new economics of industrial policy. *Annual Review of Economics*, *16*, 213–242. https://doi.org/10.1146/annurev-economics-081023-024638

Kang, H., & Song, J. (2017). Innovation and recurring shifts in industrial leadership: three phases of change and persistence in the camera industry. *Research Policy*, *46*, 376–387.

Krenz, A., Prettner, K., & Strulik, H. (2021). Robots, reshoring, and the lot of low-skilled workers. *European Economic Review*, *136*, 103744.

Kwak, K., & Yoon, H. (2020). Unpacking transnational industry legitimacy dynamics, windows of opportunity, and latecomers' catch-up in complex product systems. *Research Policy*, *49*, 103954.

Lamperti, F., Lavoratori, K., & Tredicine, L. (2025). From globalization to reshoring? The role of Industry 4.0 in global value chains across Europe. *Economics of Innovation and New Technology*. https://doi.org/10.1080/10438599.2025.2487145

Landini, F., Lee, K., & Malerba, F. (2017). A history-friendly model of the successive changes in industrial leadership and the catch-up by latecomers. *Research Policy*, *46*(2), 431–446.

Laplume, A. O., Petersen, B., & Pearce, J. M. (2016). Global Value Chains from a 3D Printing Perspective. *Journal of International Business Studies*, *47*(5), 595–609. https://doi.org/10.1057/jibs.2015.47

Lazzeretti, L., & Capone, F. (2017). The transformation of the Prato industrial district: an organisational ecology analysis of the co-evolution of Italian and Chinese firms. *The Annals of Regional Science*, *58*(1), 135–158.

Lee, K., & Ki, J. H. (2017). Rise of latecomers and catch-up cycles in the world steel industry. *Research Policy*, *46*(2), 365–375.

Lee, K., & Malerba, F. (2017). Catch-up cycles and changes in industrial leadership: Windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research Policy*, *46*(2), 338–351.

Lee, J. Y., Kim, D., Choi, B., & Jimenez, A. (2023). Early evidence on how Industry 4.0 reshapes MNEs' global value chains: The role of value creation versus value capturing by headquarters and foreign subsidiaries. *Journal of International Business Studies*, *54*, 599–630.

Lema, R., Fu, X., & Rabellotti, R. (2020). Green windows of opportunity: latecomer development in the age of transformation toward sustainability. *Industrial and Corporate Change*, *29*(5), 1193–1209.

Li, D., Capone, G., & Malerba, F. (2019). The long march to catch-up: a history-friendly model of China's mobile communications industry. *Research Policy*, *48*(3), 649–664.

Lombardi, S., & Sforzi, F. (2016). Chinese manufacturing entrepreneurship capital: evidence from Italian industrial districts. *European Planning Studies*, *24*(6), 1118–1132.

Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy*, *31*, 247–264.

Malerba, F., Nelson, R. R., Orsenigo, L., & Winter, S. G. (1999). History-friendly models of industry evolution: The computer industry. *Industrial and Corporate Change*, *8*(1), 3–40.

Malerba, F., Nelson, R. R., Orsenigo, L., & Winter, S. G. (2008). Vertical integration and disintegration of computer firms: A history-friendly model of the coevolution of the computer and semiconductor industries. *Industrial and Corporate Change*, *17*(2), 197–231.

Malerba, F., Nelson, R. R., Orsenigo, L., & Winter, S. G. (2016). *Innovation and the Evolution of Industries: History Friendly Models*. Cambridge University Press.

Martinelli, A., Mina, A., & Moggi, M. (2021). The enabling technologies of industry 4.0: examining the seeds of the fourth industrial revolution. *Industrial and Corporate Change*, *30*(1), 161–188. https://doi.org/10.1093/icc/dtaa060

Mejías, A. M., Bellas, R., Pardo, J. E., & Paz, E. (2019). Traceability management systems and capacity building as new approaches for improving sustainability in the fashion multi-tier supply chain. *International Journal of Production Economics*, *217*, 143–158. https://doi.org/10.1016/j.ijpe.2019.03.022

Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Belknap Press/Harvard University.

Park, K. H., & Lee, K. (2006). Linking the technological regime to the technological catch-up: analyzing Korea and Taiwan using the US patent data. *Industrial and Corporate Change*, *15*(4), 715–753.

Perez, C., & Soete, L. (1988). *Catching up in technology: entry barriers and windows of opportunity*. Pinter.

Pisano, G. P., & Shih, W. C. (2012). *Producing prosperity: Why America needs a manufacturing renaissance*. Harvard Business.

Schamp, E. W. (2005). Decline of the district, renewal of firms: An evolutionary approach to footwear production in the Pirmasens area. *Germany Environment and Planning A*, *37*(4), 617–634.

Scott, A. J. (2006). The changing global geography of low-technology, labor-intensive industry: Clothing, footwear, and furniture. *World Development*, *34*(9), 1517–1536.

Steinmueller, W. E. (2006). Learning in the knowledge-based economy: The future as viewed from the past. In C. Antonelli, D. Foray, B. H. Hall, & W. E. Steinmueller (Eds.), *New Frontiers in the Economics of Innovation and New Technology* (pp. 207–238). Elgar.

Strange, R., & Zucchella, A. (2017). Industry 4.0, Global Value Chains and International Business. *Multinational Business Review*, *25*(3), 174–184. https://doi.org/10.1108/MBR-05-2017-0028

Terzi, A., Sherwood, M., & Singh, A. (2023). European Industrial Policy for the Green and Digital Revolution. *Science and Public Policy*, *50*, 842–857. https://doi.org/10.1093/scipol/scad018

Tushman, M. L., & Anderson, P. (1986). Technological discontinuities and organizational environments. *Administrative Science Quarterly* 439–465.

Vértesy, D. (2017). Preconditions, windows of opportunity and innovation strategies: Successive leadership changes in the regional jet industry. *Research Policy*, *46*, 388–403.

Yap, X. S., & Truffer, B. (2019). Shaping selection environments for industrial catch-up and sustainability transitions: A systemic perspective on endogenizing windows of opportunity. *Research Policy*, *48*, 1030–1047.

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