Simmelian Brokerage in Hyperlink Networks:
How Sector–Regional Contingencies Shape Innovation Potential

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Abstract

This study explores how adopting digital technologies helps companies increase their innovation potential by building valuable connections with other firms. These benefits depend on the type of industry and the region where the company operates. Using hyperlink network as digital traces of technology use, we examined 10,653 Finnish firms across 9 industries and 19 regions. Statistical analysis shows that digital technology adoption strengthens these strategic network positions, with the strongest effects coming from advanced high-technology tools, followed by cloud computing and social media. Knowledge-intensive industries (such as broadcasting and consulting) and digitally advanced regions (such as Ahvenanmaa) benefit the most, while more traditional sectors (like hospitality) and remote regions (like Lappi) face greater limitations. When industry type and regional context align well, the positive effects become even stronger.

These findings extend network theory and the concept of dynamic capabilities by showing that digital adoption creates innovation potential through advantageous network positions. By connecting digital technology adoption with network perspectives, the study explains why digital transformation produces different innovation outcomes across sectors and regions.

Keywords

Simmelian brokerage; Innovation potential; Sectoral contingency; Regional contingency; Digital technology adoption; Network Analysis

1. Introduction

Technology adoption, especially digital technologies, has become a central driver of firm competitiveness and innovation (Apostol & Hernández-Rodríguez, 2025; Montresor & Vezzani, 2023; Sun et al., 2025). Firms increasingly rely on high-technology services, cloud computing, and social media to reconfigure resources and recombine knowledge. Despite these promises, outcomes remain uneven across firms. Some firms achieve significant innovation gains, while others face diminishing returns or even capability erosion, raising important questions about the mechanisms that translate technology adoption into innovation (Cirillo et al., 2023; Entezarkheir & Moshiri, 2025; Usai et al., 2021).

Research on digital technology adoption (DTA) emphasizes efficiency, dynamic capabilities, and organizational change (Heavin & Power, 2018; Vial, 2019), while network theory highlights how brokerage positions foster innovation by bridging diverse knowledge sources (Burt, 2004; Granovetter, 1983; Heß et al., 2025; Moon et al., 2022). This theoretical perspective extends to inter-organizational relationships as dynamic battlefields for knowledge exchange and collaborative innovation networks , where relational dynamics and inventor triads shape innovation outcomes (Alberti et al., 2021; Brattström & Faems, 2020; Nan et al., 2025). However, little is known about how adoption translates into network advantages that amplify innovation potential. Existing work also neglects contextual contingencies: adoption benefits may differ substantially across industries with varying knowledge intensity and regions with unequal digital infrastructures (Gifford et al., 2021; Leigh et al., 2022; Nan et al., 2025; You et al., 2025).

This study investigates how DTA shapes firms' innovation potential through Simmelian brokerage, a network position that balances diversity and cohesion by bridging cohesive cliques (Latora et al., 2013). Innovation potential is a firm's latent capacity to generate novel ideas and effectively recombine knowledge from various sources. This capacity exists upstream and precedes actual innovation outputs such as patents or new products (Y. Wang et al., 2025). A Simmelian brokerage position places the firm as the sole shared member between multiple otherwise disconnected cohesive groups. The unique position delivers non-redundant information together with high levels of trust and coordination. Several recent studies demonstrate that Simmelian brokerage strongly enhances innovation outcomes and the quality of idea elaboration (Tasselli et al., 2025; Tortoriello & Krackhardt, 2010). In this study we operationalize innovation potential through firms' Simmelian brokerage scores in the hyperlink network. We measure adoption using external hyperlinks as digital traces of firms' connections to high-technology services, social media platforms, and cloud providers (Plekhanov et al., 2023). Although smaller economies such as Italy and Norway, have been studied in network-DTA adoption driven innovation, the discourse is still dominated by larger economies like China and the USA (Alberti et al., 2021; Rypestøl et al., 2022; Shao & Xu, 2025). This study turns to a small Nordic country, Finland, to offer fresh perspectives. Analyzing a dataset of 10,653 Finnish firms across nine sectors and nineteen regions, we construct a network of 129,737 ties and apply linear mixed-effects models to identify context-specific effects.

The results show that DTA enhances brokerage and thus innovation potential, with high-technology adoption as the strongest driver, followed by cloud computing and social media. Crucially, these effects are contingent on regions, industries and their intersections. By linking digital technology adoption to network theory and contextual contingencies, this study clarifies how the adoption produces heterogeneous outcomes and offers actionable insights for managers and policymakers.

2. Theoretical Background and Hypotheses Development

2.1 Digital Technology Adoption and Innovation

Digital technology adoption refers to the strategic integration of information, computing, communication, and connectivity technologies to transform organizational processes and capabilities (Vial, 2019). Such integration enhances operational efficiency while enabling firms to respond more effectively to dynamic market conditions through innovation. Based on the "integration of digital technology" dimension of the Digital Economy and Society Index (European Commission, 2022), this study focuses on three core digital technologies: social media, cloud computing, and advanced information technology research and development (hereafter shorten to high-tech). These technologies are widely recognized as key drivers of innovation and competitive advantage across industries (Molinillo & Japutra, 2017; Skare et al., 2023).

The adoption of digital technologies facilitates innovation by improving resource coordination and enabling new knowledge creation, therefore strengthening dynamic capabilities related to both exploration (e.g., R&D activities) and exploitation (e.g., patenting) (Heavin & Power, 2018; Jafari-Sadeghi et al., 2021). Empirical evidence demonstrates positive innovation outcomes across diverse contexts, including green innovation in Chinese manufacturing firms (Shao et al., 2024), business model innovation and performance in Spanish firms (Merín-Rodrigáñez et al., 2024), and healthcare innovation enabled by blockchain-based data management systems (Massaro, 2023). Similarly, the adoption of Industry 4.0 technologies promotes open innovation and enhances product and process development, particularly when supported by collaborative R&D arrangements (Kim & Park, 2024).

However, innovation gains from digitalization are neither automatic nor uniform. Implementation complexity, organizational inertia, and resource constraints may limit firms' ability to convert technological investments into financial or innovative returns (Fitzgerald et al., 2013; Zhai et al., 2022). The effectiveness of such adoption is further shaped by absorptive capacity and complementary ICT investments, which determine how effectively firms internalize and exploit digitally enabled knowledge (Jafari-Sadeghi et al., 2021; X. Wang et al., 2024). The Technology–Organization–Environment (TOE) framework and diffusion of innovation theory provide complementary explanations, emphasizing technological compatibility, organizational readiness, and external pressures such as competition as key determinants of adoption outcomes (Faiz et al., 2024; Molinillo & Japutra, 2017). Evidence from Italian firms highlights these dynamics, showing uneven Industry 4.0 adoption patterns that are closely linked to workforce education levels and human capital endowments (Cirillo et al., 2023; Montresor & Vezzani, 2023).

Beyond firm-level outcomes, digital technologies also support cross-industry innovation by enabling collaboration and data integration across sectoral boundaries, thereby addressing complex societal and technological challenges (Kerstens & Langley, 2025). Intermediaries play a central role in this process by enhancing absorptive capacity and facilitating inter-organizational knowledge exchange. Nevertheless, excessive reliance on digital interactions may weaken relational capital and undermine long-term innovation if it displaces trust-based relationships (Usai et al., 2021). Moreover, delayed adoption can be exacerbated by unfavorable consumer perceptions or negative word-of-mouth, slowing the diffusion of digital innovations (Jahanmir & Cavadas, 2018).

2.2 Network Perspective on Innovation

Network theory emphasizes that inter-organizational relationships provide access to non-redundant knowledge, thereby fostering breakthrough innovation through mechanisms such as structural holes and brokerage (Burt, 2004; Granovetter, 1983). Brokerage positions within knowledge networks, for example, those formed through co-authorship or collaborative R&D, enable firms to access diverse information sources and are associated with higher innovative output, including increased patenting. However, the benefits of knowledge diversity are subject to absorption limits, resulting in an inverted U-shaped relationship in which excessive heterogeneity can overwhelm firms' integration capacities (Heß et al., 2025).

The effectiveness of network configurations depends strongly on contextual conditions. In triadic alliances, strong ties promote trust and reduce relational risks, while weak ties introduce novel knowledge, with absorptive capacity moderating their combined effects (Kerstens & Langley, 2025; Moon et al., 2022; Nan et al., 2025). Within industrial clusters, structural holes facilitate information arbitrage and diversity but may hinder integration when trust is insufficient, reflecting the influence of social and political embeddedness (Alberti et al., 2021; You et al., 2025). Similarly, ego-network studies show that moderate network stability optimizes individual innovation, whereas excessive stability constrains creativity, particularly under high technological complexity (Lin et al., 2022) .

Brokerage occupies a central position in network-based explanations of innovation and is commonly operationalized through the concept of structural holes, measured using Burt's constraint index or betweenness centrality (Choi et al., 2022; Heß et al., 2025; Moon et al., 2022; Nan et al., 2025). Digital technologies enhance the effectiveness of these brokerage positions by facilitating knowledge flows and lowering coordination costs across organizational boundaries (Garrido-Moreno et al., 2024; Plekhanov et al., 2023). Empirical evidence illustrates this dynamic in contexts such as patent collaboration networks in urban rail transit, where modularization and clustering reflect digitally enabled organizational transformation (Y. Wang et al., 2025), and in Research and Technology Organizations in the

US and UK, which act as intermediaries coordinating innovation across digital manufacturing networks (Anzolin & O'Sullivan, 2025).

Recent research further underscores the role of DTA in network-driven innovation. Cross-industry intermediaries enhance absorptive capacity by enabling firms to integrate heterogeneous data sources, while platform ecosystems facilitate stakeholder collaboration and knowledge exchange at the industry level (Kerstens & Langley, 2025). Digital affordances, including collaboration and process management tools, also support ambidextrous innovation by balancing exploration and exploitation, which in turn strengthens organizational resilience (Sun et al., 2025). In China's high-speed train industry, digitally supported knowledge management systems promote both internal recombination and external knowledge acquisition, with managerial expertise moderating these effects (Jiang et al., 2025).

2.3 Contingencies of Innovation

The innovation potential generated through DTA within inter-organizational networks is strongly conditioned by contextual contingencies, particularly sectoral and regional differences that shape network density, embeddedness, and access to resources (Bertello et al., 2024; Brenner et al., 2013; You et al., 2025). These contingencies influence the extent to which digitalization translates into meaningful innovation outcomes, underscoring the need for context-sensitive strategies.

Sectoral characteristics play a critical moderating role. Knowledge-intensive industries, such as high-technology services and healthcare, are better positioned to leverage brokerage roles and diverse knowledge ties, thereby strengthening absorptive capacity and supporting complex knowledge recombination (Li et al., 2025; Moon et al., 2022). In healthcare, for example, digital solutions tailored to local needs have reduced rural disparities in India, illustrating sector-specific innovation pathways (Devi et al., 2025). In manufacturing, Industry 4.0 adoption promotes coupled open innovation, particularly in R&D-intensive activities where collaboration accelerates product and process development (Kim & Park, 2024). By contrast, less knowledge-intensive sectors often rely on denser and more homogeneous networks, facing higher integration costs and weaker innovation effects due to limited knowledge diversity (Lin et al., 2022).

Regional conditions further shape these dynamics. Areas with well-developed digital and network infrastructure facilitate efficient knowledge flows and amplify innovation potential. Urban regions, such as Espoo in Finland, function as collaborative innovation platforms that leverage user involvement to support digitalization and localized ecosystem development (Gifford et al., 2021; Tukiainen et al., 2015). Similarly, Digital Innovation Hubs in Italy's Marche region enable micro, small, and medium enterprises to access technological expertise and network resources, lowering adoption barriers (Marinelli et al., 2024). In contrast, peripheral or underdeveloped regions face higher adoption costs and diminished innovation returns due to infrastructural constraints and limited network connectivity (Trinugroho et al., 2022).

Interactions between sectoral and regional conditions can generate reinforcing effects. Knowledge-intensive activities located in resource-rich urban regions benefit from dense networks and diverse knowledge pools, as evidenced in healthcare blockchain applications (Massaro, 2023) and patent collaboration networks in China's urban rail transit sector (Y. Wang et al., 2025). Broader evidence from the Asia–Pacific region indicates that digitalization-driven growth varies across urban–rural divides due to differences in infrastructure and globalization (Elfaki & Ahmed, 2024). Firm-level studies in Indonesia and Italy further demonstrate how age, size, and sectoral knowledge intensity interact with regional infrastructure to shape adoption patterns and innovation outcomes (Cirillo et al., 2023; Trinugroho et al., 2022). Intermediaries can partially offset these constraints by fostering cross-industry collaboration and enabling access to diverse knowledge networks.

2.4 Hypotheses Development

Building on the preceding discussion, we develop hypotheses to examine how DTA influences innovation potential within inter-organizational networks, with effects contingent on sectoral and regional conditions and their interaction. Rather than focusing on realized innovation outcomes, this study conceptualizes innovation potential as a latent capacity captured through Simmelian brokerage. Simmelian brokerage reflects the ability to bridge cohesive groups while maintaining external ties, facilitating novel knowledge inflows without undermining trust (Latora et al., 2013; Valeri & Baggio, 2022). Unlike traditional brokerage, which emphasizes access to diverse information through structural holes (Burt, 2004; Kim & Park, 2024) , this form of brokerage balances cohesion and diversity, a configuration particularly relevant in digitally mediated networks (Tasselli et al., 2025) .

Focusing on Finnish firms, hyperlink networks are used to assess how digital technologies, including high-tech, social media, and cloud computing, shape network positions that combine cohesion and diversity. By strengthening dynamic capabilities and inter-organizational ties, such technologies enable firms to bridge cohesive clusters and access non-redundant knowledge.

Hypothesis 1: Digital technology adoption positively affects innovation potential through Simmelian brokerage positions.

Hypothesis 2: The effect of digital technology adoption on innovation potential varies by sector, with stronger effects in knowledge-intensive sectors.

Hypothesis 3: The effect of digital technology adoption on innovation potential varies by region, with stronger effects in Finland's urban regions.

Hypothesis 4: Sector–region interactions moderate the effect of digital technology adoption on innovation potential, with amplified effects in knowledge-intensive sectors located in resource-rich urban regions.

3. Data and Method

We collected data on firms' external hyperlinks from their public websites to construct the inter-organizational network. This study uses hyperlinks as digital traces of technology adoption rather than relying on survey instruments. Hyperlinks capture firms' actual behavioral decisions to connect to high-technology services, cloud providers, and social media platforms. Survey methods, by contrast, can offer valuable information on internal adoption depth, implementation processes, employee skills, and managerial perceptions that public hyperlinks cannot reveal. However, surveys are subject to low response rates, recall bias, social desirability bias, and inaccurate network reporting, which can severely distort brokerage measures in large-scale studies (Salganik, 2018). For the present research questions, which focus on how observable digital adoption shapes objective network positions and innovation potential across sectors and regions, hyperlink data provide a more objective and comprehensive approach (Abbasiharofteh et al., 2023).

We only collect publicly available company-level information: the company's website, location, and industry sector. No sensitive data such as employee details or financial information is collected or published. The study relies exclusively on external hyperlinks, and the unit of analysis is the firm rather than the individual. As a result, no personally identifiable information was collected, stored, or analyzed, which minimizes privacy risks and ensures compliance with relevant data protection standards. In addition, the automated web scraping process was designed to be minimally intrusive. Data collection was restricted to public-facing content and limited to a defined domain depth in order to respect the digital infrastructure of the targeted organizations.

As a global digital frontrunner, Finland serves as a lead market case study. While its high digitalization may limit direct generalizability to emerging economies, it provides an ideal living lab to establish the upper boundaries of what is possible when digital technology adoption is mature, offering a benchmark for countries with developing infrastructures. The analysis targets customer-oriented sectors, aligning with studies on service-intensive industries (Jafari-Sadeghi et al., 2021; Moon et al., 2022).

3.1 Data Collection and Preprocessing

The primary data were sourced from Orbis Europe, which provides detailed firm-level information on European companies, including sector classifications, regional locations, and website URLs. From this database, we initially extracted records for 85,845 Finnish companies distributed across nine customer-oriented sectors: architecture and design, art and culture, broadcasting and publishing, consulting and marketing, event and support, gaming and sports, hotel and food services, music and film, and passenger transport. These sectors represent some of Finland's most dynamic cultural, creative, and service-oriented industries. For instance, architecture and design are internationally recognized for their minimalist aesthetics and functional innovation, while art and culture cover Finland's strong institutional and grassroots traditions in visual arts, performing arts, and heritage. Broadcasting and publishing remain central to Finland's media landscape, reflecting both the country's historic newspaper culture and its digital transformation. Meanwhile, consulting and marketing capture Finland's growing expertise in design thinking, branding, and IT-based consulting, and the event and support services sector underpin the organization of cultural festivals, fairs, and professional gatherings that sustain creative ecosystems. The gaming and sports sector is particularly vibrant, with global successes such as Rovio and Supercell placing Finland among the world's top gaming hubs, while hotel and food services highlight the close link between tourism, hospitality, and regional economies. Music and film constitute another globally visible sector, supported by national institutions and a strong export orientation, whereas passenger transport plays a foundational role in enabling accessibility and mobility across Finland's vast geography.

The companies in our dataset are distributed across all 19 Finnish regions (see details at Table 2 in Appendix). While urban regions such as Uusimaa, Pirkanmaa, and Varsinais-Suomi concentrate a high share of companies due to their metropolitan hubs (Helsinki, Tampere, Turku), more rural regions such as Lappi, Kainuu, Etelä-Savo and Ahvenanmaa also contribute significantly, especially in sectors like tourism, events, and passenger transport. This regional spread ensures that the analysis captures both metropolitan innovation clusters and peripheral creative economies, reflecting Finland's dual urban–rural industry structure.

To construct a hyperlink network, we focused on companies with active websites, excluding those without URLs and removing duplicates, resulting in a final sample of 10,653 companies. This preprocessing step ensured data quality and relevance to digital adoption, as websites serve as proxies for digital presence and interconnections (Apostol & Hernández-Rodríguez, 2025; Plekhanov et al., 2023). We built the hyperlink network using each company's homepage as a seed node. Employing Domain-Restricted Breadth-First Search Scraping (Bundy & Wallen, 1984), we explored each website up to the 4th level, collecting external hyperlinks while excluding intra-domain links.

The scraping procedure began with a predefined seed website, such as Santa's Hotels (santashotels.fi), which served as the starting node for automated navigation. Next, an automated scraper visited the homepage and recursively followed embedded hyperlinks up to four clicks deep, for example reaching subpages such as https://santashotels.fi/en/hotels/rovaniemi-hotel-santa-claus/rooms . During this process, a strict filtering rule was applied to exclude intra-domain links, meaning that links remaining within the same website (e.g., https://bookings.santashotels.fi/search-rates) were ignored. Only hyperlinks leading to external domains were recorded, such as https://pyha.fi . As a result, the scraper identified that Santa's Hotels connected digitally to external actors including Pyhä (a ski resort in northern Finland) and social media platforms such as LinkedIn. These outbound hyperlinks were then conceptualized as "edges" representing inter-organizational digital relationships within a broader tourism-related web network.

In the resulting directed network, seed companies are starting nodes, external domains are target nodes, and hyperlinks represent edges. The final network comprises 10,653 nodes and 102,329 edges, capturing inter-firm digital connections.

3.2 Variables and Simmelian brokerage Algorithm

The dependent variable is Simmelian brokerage, a network metric for innovation potential that quantifies a node's position bridging multiple cohesive groups.

The Simmelian brokerage metric is defined as:

$B_i = k_i - (k_i - 1)E_{loc,i}$

$$E_{loc,i} = \frac{1}{N}\sum_{i \in G} E(G_i)$$

Where:

B_i is the Simmelian brokerage score for node *i,*

k_i is the degree of node *i,*

$E_{loc,i}$ is the local efficiency of node *i,*

G_i is the subgraph of the neighbours of node *i.*

Local (nodal) efficiency E_{loc} defined as the inverse of the harmonic mean of the minimum path length d_{ij} between node i, and the nodes in its immediate neighborhood. This measure captures the balance of diversity and cohesion, extending traditional brokerage such as betweenness centrality by emphasizing clique-bridging for knowledge recombination, as seen in inventor triads and competition networks. For example (see in Figure 1), “North-Consult” is embedded in a tightly connected clique of five Helsinki firms, which builds trust but also creates redundant information. However, it also holds a unique external hyperlink to an AI research lab elsewhere, enabling access to novel knowledge while remaining anchored in a cohesive cluster. This brokerage position is measured by $B_i = k_i - (k_i - 1)E_{loc,i}$, where high values indicate strong connectivity (k_i) combined with low neighbor interconnection ($E_{loc,i}$), reflecting an optimal mix of stability and innovation access.

This brokerage position is captured by Simmelian brokerage, where higher values reflect strong local connectivity combined with weak interconnection among neighbors. Importantly, betweenness centrality does not capture this pattern. Firms A, B, and C within the clique have zero betweenness because they do not lie on shortest paths, yet they still show a brokerage value of 1 under Simmelian brokerage. Although their brokerage capacity is much smaller than North-Consult, the measure recognizes clique-based bridging that betweenness (value 0.00) fails to detect.

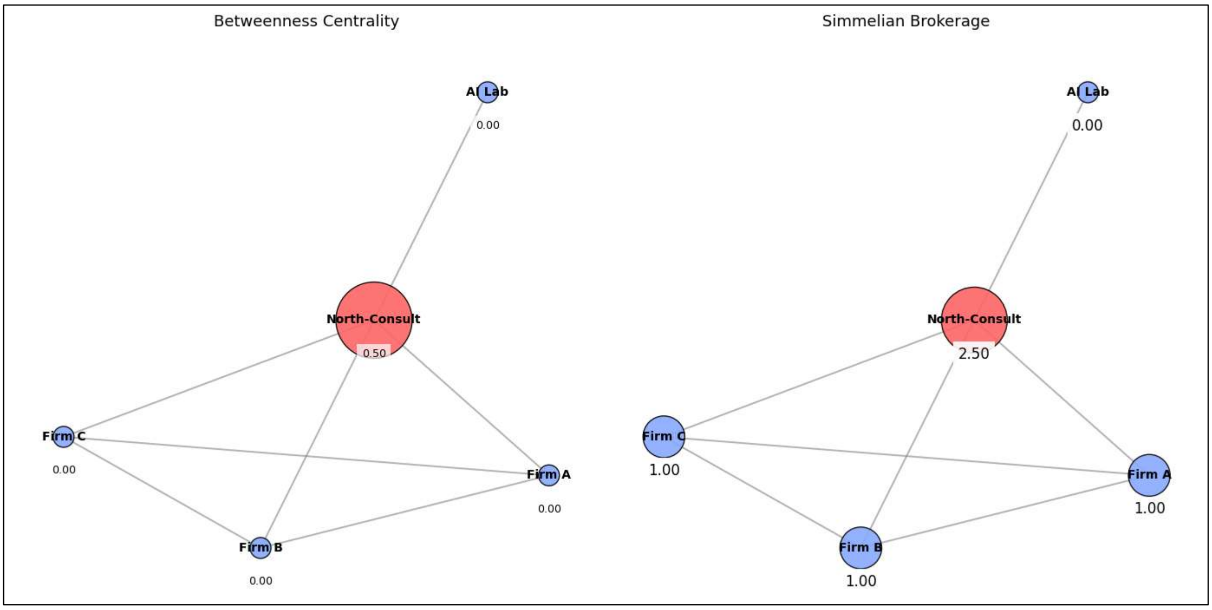

Figure 1 Simmelian Brokerage Vs Betweenness Centrality: The North-Consult Example

Independent variables are the adoption rates for high-tech, social media, and cloud computing, derived from hyperlink counts. Although social media and cloud computing rely on advanced ICT foundations, they are modeled separately in this study to capture distinct firm-level adoption patterns and their unique contributions to hyperlink-based brokerage. This approach also aligns with empirical classifications in digital adoption research, such as the DESI categories of integration of digital technology (European Commission, 2022; Skare et al., 2023). It is measured across three dimensions:

1. High-technology adoption (HTA): captured through links to firms in electronic manufacturing, telecommunications, IT services, and scientific R&D (e.g., Nokia in telecommunications, Tietoevry in IT services, and VTT Technical Research Centre in R&D).

2. Cloud computing adoption: reflecting the use of online infrastructure, storage, and content delivery networks that provide scalable and flexible digital services (e.g., Amazon Web Services, Google Cloud, Microsoft Azure, or Cloudflare).

3. Social media adoption: indicating firms' presence on interactive platforms that support communication, customer engagement, and digital visibility (e.g., Facebook, Instagram, LinkedIn, Twitter/X, or customer-centered social media platform such as Tripadvisor) (Koski et al., 2019).

Grouping variables include sector (9 categories) and region (19 categories), treated as random effects to account for hierarchical clustering. To ensure that larger firms with complex websites do not naturally achieve higher scores simply by having more links, we control for degree centrality (the same connections only counted once). This ensures that the Simmelian brokerage score reflects the strategic quality of a firm's network position, acting as a trusted bridge rather than the raw size of its digital footprint.

3.3 Analytical Method and Robustness Check

Given the hierarchical structure of the data (firms nested within sectors and regions), we employed linear mixed-effects models (LMM), which extend ordinary least squares (OLS) regression by incorporating fixed and random effects (Harrison et al., 2018). LMM is suitable for analyzing clustered data, capturing both population-level effects (e.g., technology adoption) and group-specific variations (e.g., sectoral heterogeneities).

The general LMM model is:

$y = X\beta + Zu + \epsilon$

Where:

y is the vector of the dependent variable (brokerage).

X is the design matrix for the fixed effects.

β is the vector of fixed-effect coefficients (for technology, social, cloud).

Z is the design matrix for the random effects.

u is the vector of random-effect coefficients (for region or sector).

ϵ is the vector of residuals (errors).

We estimated three models (Figure 2): (1) random effects by sector, (2) by region, and (3) by sector-region interaction. Prior to estimation, we assessed multicollinearity among fixed effects using a correlation matrix and variance inflation factors (VIF), confirming no issues (all VIF < 5). Residual diagnostics included kernel density estimates (KDE), Q-Q plots, and skewness tests to verify normality assumptions. Analyses were conducted in Python using libraries e.g., statsmodels and networkx, ensuring reproducibility in a REPL environment.

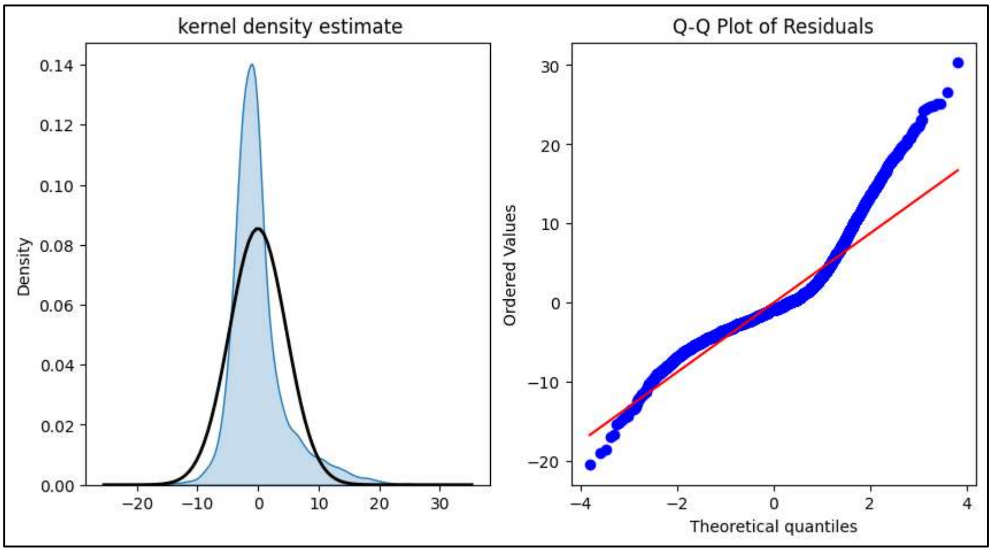

Figure 2 Model Evaluation KDE and Q-Q plot

To ensure the reliability of results, we conducted several robustness tests. First, alternative specifications included log-transforming the dependent variable to address potential skewness, yielding consistent fixed effects (e.g., technology $\beta \approx 2.7$, $p < 0.001$). Second, sensitivity analyses excluded outliers (top/bottom 1% of brokerage scores) with minimal changes in coefficients, aligning with firm-level robustness in patent-based studies (Heß et al., 2025; Lin et al., 2022).

Third, validation against baseline OLS models showed improved fit for LMM (lower AIC/BIC), and intraclass correlation coefficients (ICC) validated random effects. These checks affirm the model's robustness, consistent with methodological rigor in network-innovation research (Moon et al., 2022; Nan et al., 2025).

4. Results and Discussion

This section presents the results from the linear mixed-effects models (LMMs) examining the relationship between digital adoption (high-technology, social media, and cloud computing) and Simmelian brokerage as a measure of innovation potential. Three LMMs (Table 1) were estimated to evaluate the hypotheses: Model 1 with random effects by sector, Model 2 by region, and Model 3 by sector-region interaction.

	Intercept_coef	High-tech_coef	Social_coef	Cloud_coef	Observations	Group size	Random variance	ICC
Sector Model	1.497	2.689	0.877	1.344	10653	9	0.53	0.024
Region Model	1.352	2.701	0.883	1.37	10653	19	0.05	0.002
S-R Model	1.41	2.69	0.881	1.349	10653	171	0.452	0.02

Table 1 Summary of Linear Mixed-Effects Models

4.1 Fixed Effects Results and Discussion

The fixed effects across all models support Hypothesis 1, showing that DTA positively influences innovation potential, as measured by Simmelian brokerage. High-technology adoption exhibits a robust coefficient ($\beta \approx 2.7$, $p < 0.001$), enabling diverse knowledge access through brokerage positions. This relationship occurs because advanced digital tools function as “sensing and seizing” mechanisms (Li et al., 2025) that allow firms to identify and capture non-redundant knowledge while maintaining the cohesive cliques necessary for internal trust. This suggests that DTA facilitates innovation not merely through resource management (Heavin & Power, 2018), but by specifically reconfiguring the firm’s digital traces to act as a trusted bridge between disconnected social clusters. While Fitzgerald et al. (2013) identify “implementation traps” like lack of vision and funding, our results suggest that when firms successfully integrate these technologies, they overcome organizational inertia by establishing a digital infrastructure that balances cohesion and diversity. While Usai et al. (2021) find that digital technologies exert only a “mild impact” and can deplete long-run capability by standardising knowledge and reducing cross-fertilisation, our findings demonstrate a robust linear effect on innovation potential. This discrepancy is likely sample-related and methodological; Usai et al. (2021) focused on radical "world-first" innovation outputs in European firms, whereas our study conceptualises innovation potential as a latent network property (Simmelian brokerage). This suggests that while DTA might codify explicit knowledge, it simultaneously extends a firm’s capacity to sense and seize new network opportunities, corroborating the digital dynamic capabilities framework (Jafari-Sadeghi et al., 2021).

Cloud computing adoption ($\beta \approx 1.35$, $p < 0.001$) supports scalable infrastructure for knowledge integration (Jafari-Sadeghi et al., 2021), consistent with its facilitation of green innovation in manufacturing (Shao et al., 2024) and healthcare innovation via blockchain (Massaro, 2023). However, this robust positive effect represents a theoretical extension of the uneven adoption patterns. Cirillo et al. (2023) argue that structural features like firm size and lack of skills act as significant barriers to adoption, particularly for micro-firms. Social media adoption ($\beta \approx 0.88$, $p < 0.001$) fosters weaker ties for information diversity, aligning with its drive of competitive advantage (Molinillo & Japutra, 2017) and collaborative R&D in Industry 4.0 (Kim & Park, 2024). This positive finding faces a contextual boundary condition when compared to Jahanmir and Cavadas (2018), who identify “skepticism and resistance” as determinants of slow diffusion among late adopters. Theoretically, this implies that while social media adoption provides the potential for brokerage, the “relational risks” and negative attitudes present in a firm's network may limit the actual recombination of knowledge into breakthrough innovations (Moon et al., 2022).

These effects highlight DTA's contingent nature, shaped by technological compatibility and organizational readiness in the TOE framework, and moderated by sectoral and regional factors. Nonetheless, causality is ambiguous, as self-selection into DTA may inflate effects (Zhai et al., 2022). This finding extends network theory by showing digitalization empowers Simmelian brokerage to balance cohesion and diversity (Latora et al., 2013; Tasselli et al., 2025), emphasizing cross-industry collaboration. Managers should prioritize integrated digital strategies to enhance absorptive capacity, addressing barriers like resource constraints to sustain innovation.

4.2 Random Effects by Sector and Discussion

The sectoral random effects from the linear mixed-effects models support Hypothesis 2, which posits that DTA influences Simmelian brokerage differently across sectors (Figure 3), with stronger effects in knowledge-intensive industries.

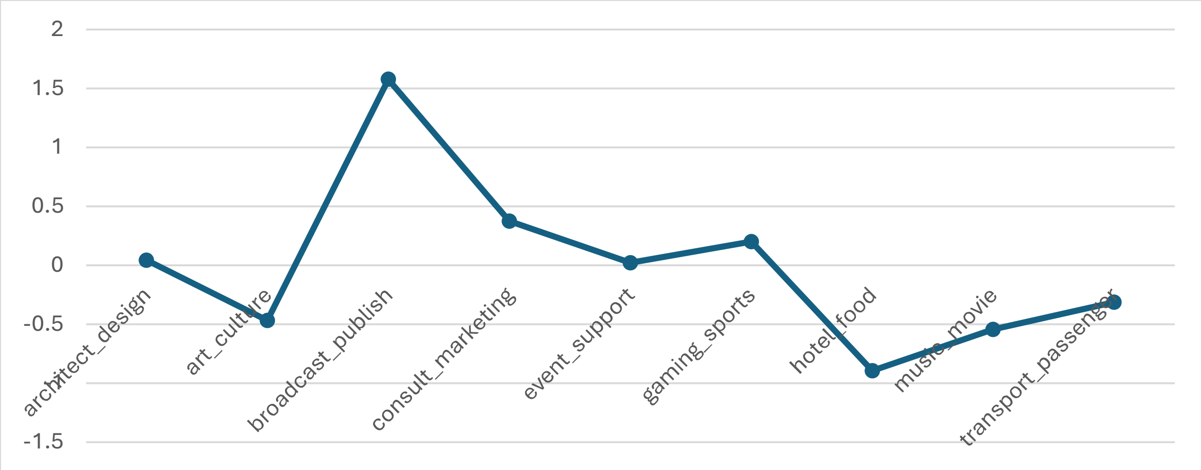

Figure 3 Sector Random Effect

Broadcasting and publishing exhibits the strongest positive deviation, demonstrating that DTA significantly enhances Simmelian brokerage in this knowledge-intensive sector. This positive linear effect extends the work of Burt (2004) on information advantages but represents a methodological disagreement with the inverted U-shaped findings of Heß et al.(2025). Heß et al. (2025) argue that beyond a certain threshold, integration costs rise exponentially, leading to diminishing returns. This divergence is explained by the knowledge integration cost dynamic. While Heß et al. (2025) focus on the dense, technical standard-setting networks of the chemical industry where "technological distance" creates high cognitive friction, Finnish creative sectors utilize DTA in sparse but clustered networks where information is more modular and less costly to recombine. The findings advance our understanding by showing that sector-specific architectural knowledge determines whether a firm can leverage brokerage as an asset or if it becomes a net drag on innovation due to complexity

Consulting and marketing follows with a notable positive deviation, reflecting high absorptive capacity that supports knowledge recombination through digitalization driven by organizational factors such as top management support (Faiz et al., 2024). Gaming and sports shows a moderate positive deviation, leveraging digital brokerage; this aligns with network theory's emphasis on weak ties for innovation.

Architecture and design and event and support exhibit marginal positive deviations, suggesting limited brokerage gains. Hotel and food services displays the largest negative deviation, reflecting dense, localized networks that restrict DTA-driven diversity. However, this does not linearly correspond with closed structures amplifying DTA's innovation benefits in less knowledge-intensive firms (Li et al., 2025). This discrepancy is likely sample-related; Li et al. (2025) focused on Chinese firms and CEOs where "clan culture" provides a unique institutional trust mechanism, whereas we only focus on the non-human hyperlinks network. Music and movie, and art and culture also show negative deviations, indicating DTA's limited impact on brokerage in these creative sectors. Passenger transport faces similar constraints, as physical infrastructure limits digital tie expansion (Y. Wang et al., 2025).

These findings confirm Hypothesis 2, showing that DTA's effect on Simmelian brokerage is stronger in knowledge-intensive sectors like broadcasting, consulting, and gaming, where higher absorptive capacity and tie diversity facilitate innovation (Lin et al., 2022; Moon et al., 2022). The failure of DTA to boost brokerage in less knowledge-intensive sectors stems from "structural churn" i.e., in traditional sectors (Lin et al., 2022), network stability is often over-pursued, leading to path dependence that digital tools cannot easily break. By contrast, knowledge-intensive sectors use DTA to maintain optimal network stability, allowing for the entry of new ideas while preserving the Simmelian trust necessary for collaboration. Managers in knowledge-intensive sectors should prioritize digital investments in cloud platforms and social media to amplify brokerage. In sectors with negative deviations, hybrid networks combining digital and traditional ties can mitigate limitations. Policymakers should support less knowledge-intensive sectors with DTA training to enhance absorptive capacity.

4.3 Random Effects by Region and Discussion

The regional random effects from the linear mixed-effects models partially support Hypothesis 3, positing that DTA influences innovation potential differently across Finland's 19 regions (Figure 4), with stronger effects in urban areas due to robust digital infrastructure. Ahvenanmaa exhibits the strongest positive deviation, indicating that significantly enhances Simmelian brokerage despite rural status. This finding extends the "globalization-innovation" nexus proposed by Elfaki and Ahmed (2024), who argue that globalization acts as a channel for digital technology adoption to transform an economy into a sustainable digitalized system. Our results suggest that regional "infrastructure readiness" serves as a critical boundary condition for H3. In Ahvenanmaa, successful policy integration similar to the "smart specialization" maritime cluster efforts in Sweden identified by Gifford et al. (2021), which appears to have created an "innovation ecosystem" where top-down digital incentives synergy with bottom-up entrepreneurial activity to maintain strategic brokerage. Kanta-Häme and Etelä-Savo also show positive deviations, supporting the view that localized interventions can overcome geographic constraints by facilitating entrepreneurial discovery and niche path development (Devi et al., 2025).

Uusimaa shows a modest positive deviation, suggesting diminishing returns from high baseline digitalization against assumptions of linear adoption benefits (Jafari-Sadeghi et al., 2021). Pirkanmaa and Varsinais-Suomi exhibit negative or near-neutral deviations, revealing a contextual disagreement with the "brokerage view" of innovation. While standard theories (Burt, 2004) suggest that strategic positions always yield advantages, our finding suggests that in saturated urban networks, brokers may encounter "action problems" or information overload, effectively turning potential brokerage into a liability (You et al., 2025). Lappi registers the largest negative deviation, as geographic isolation constrains DTA's potential (Trinugroho et al., 2022). This result aligns with infrastructure limitations in remote regions. Satakunta and Pohjanmaa show negative deviations, might emphasise trust in localized networks.

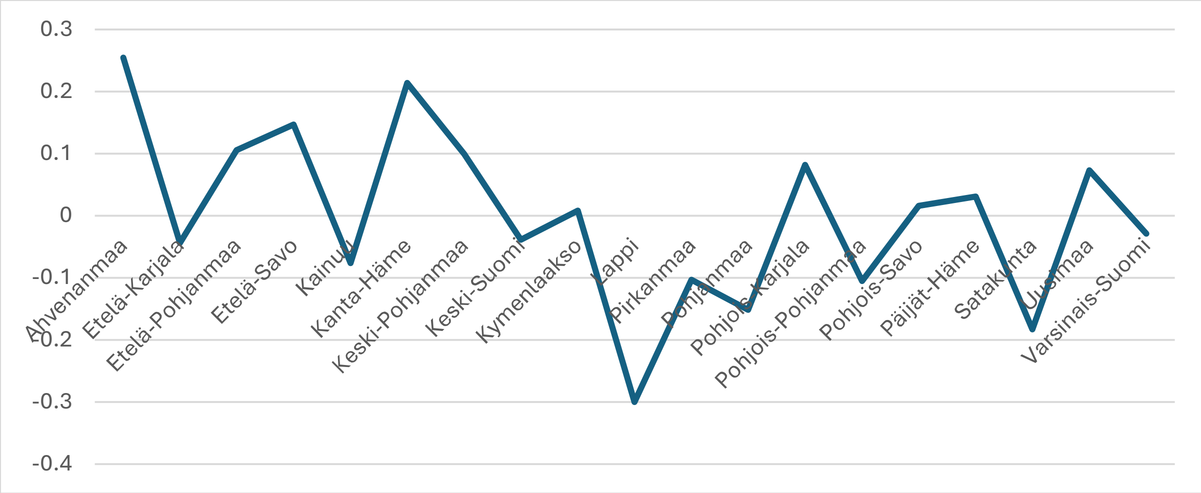

Figure 4 Region Random Effect

Rural regions like Etelä-Pohjanmaa, Keski-Pohjanmaa, and Pohjois-Karjala display positive deviations, indicating targeted initiatives enhance brokerage. This result occurs because "local information density" in these clusters creates strong collaborative norms; DTA lowers the establishment costs of the digital connections required to comply with these local expectations. Conversely, the negative deviations in Kainuu and Keski-Suomi reflect network saturation or isolation traps. Where infrastructure is lagging (Elfaki & Ahmed, 2024), DTA cannot provide the bandwidth necessary to bridge external clusters, leaving firms in myopic local networks. Near-neutral deviations in Kymenlaakso, Päijät-Häme, and Pohjois-Savo suggest limited effects in mixed sectors (Bertello et al., 2024; Brenner et al., 2013).

These findings confirm Hypothesis 3, demonstrating that DTA's effect on Simmelian brokerage varies by region, moderated by infrastructure, distance, and industry profiles. Urban and geo-central regions leverage ecosystems for knowledge recombination (Moon et al., 2022), while saturation or isolation highlights non-linear effects (Lin et al., 2022). The results extend network theory by illustrating Simmelian brokerage's role in mitigating constraints. Managers in regions like Ahvenanmaa should invest in cloud computing and social media to enhance brokerage. In regions like Lappi, partnerships with digital hubs can build network capital. Policymakers should prioritize infrastructure and regional hubs to reduce disparities and promote innovation.

4.4 Sector-Region Interactions and Discussion

The analysis of sector-region interactions supports Hypothesis 4, constituting the paper's primary empirical contribution. The dynamic at play here is Dual Embeddedness; when a knowledge-intensive firm operates in a resource-rich region, DTA resolves the action problem of brokerage by providing the security and trust protocols needed to bridge silos without violating local collaborative norms. Results reveal variation across sectors and regions, with random effects from –1 to +1.8 (Figure 5). Approximately half yield positive deviations, enhancing brokerage and innovation potential, while the remainder show negative deviations, underscoring barriers such as resource misalignment or network saturation. These negative interactions represent contextual misalignment. In highly-coordinated clusters with high political connection importance, brokers may forgo positional benefits to maintain strategic gatekeeper status, effectively turning DTA into a liability (You et al., 2025). This finding significantly advances conceptual understanding by demonstrating that Simmelian brokerage is a double-edged sword whose value is determined by the intersection of sectoral knowledge intensity and regional normative pressures.

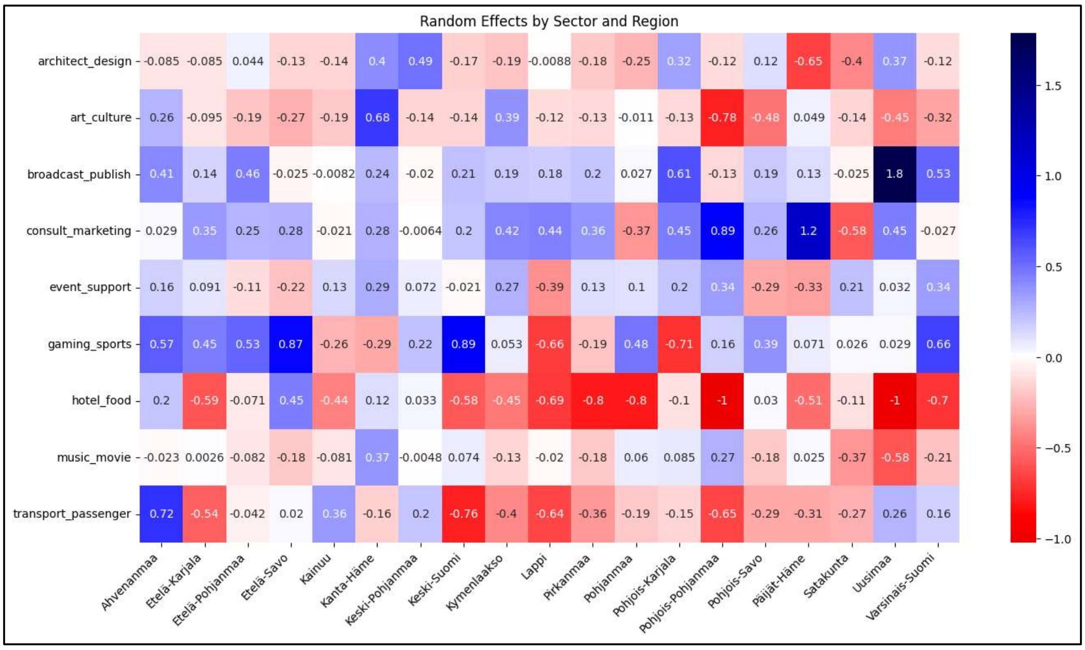

Figure 5 Sector-Region Random Effect

Knowledge-intensive sectors in urban regions display the strongest positive interactions. Broadcasting and publishing in Uusimaa amplifies clique-bridging positions through adopting digital technology. This finding represents a contextual disagreement with the inverted U-shaped relationship between brokerage and innovation output. Heß et al. (2025) argue that beyond a certain threshold, “integration costs” rise exponentially due to combinatorial effort, particularly in dense industrial network. Consulting and marketing in Pohjois-Pohjanmaa enhances absorptive capacity via tech ecosystems, however differing from challenges in less knowledge-intensive firms (Jafari-Sadeghi et al., 2021; Lin et al., 2022). Gaming and sports in Etelä-Savo strengthens brokerage despite geographic constraints (Devi et al., 2025). This result confirmed tailored digital interventions overcoming rural barriers, while contrasting with higher integration costs in remote areas (Trinugroho et al., 2022).

Conversely, less knowledge-intensive sectors or regions with limited infrastructure exhibit negative interactions. Hotel and food services in Uusimaa and Pohjois-Pohjanmaa reduce brokerage benefits due to saturation or localized networks. This however does not reflect with brokerage facilitating diverse flows in clusters (Alberti et al., 2021). These sectors’ physical dependencies limit DTA's diverse ties, reflecting integration challenges in service industries but differing from amplified benefits in clan-based networks (Kerstens & Langley, 2025). Passenger transport in Lappi shows weaker effects, as infrastructure constraints hinder digital expansion (Y. Wang et al., 2025), however not reflecting with efficient knowledge flows in urban centers (Gifford et al., 2021).

These findings confirm Hypothesis 4, demonstrating that sector-region synergies amplify DTA's effect on Simmelian brokerage in knowledge-intensive sectors within resource-rich regions (Moon et al., 2022), while barriers in saturated or remote contexts reflect closure arguments. The results extend network theory by emphasizing Simmelian brokerage's role in balancing cohesion and diversity (Tasselli et al., 2025) and refine dynamic capabilities by illustrating contextual alignment's influence on outcomes (Bertello et al., 2024; Brenner et al., 2013). Ultimately, these interactions prove that digital transformation is not a magic ingredient but a structural catalyst whose innovation potential is unlocked only when industry type and regional infrastructure align to support a trusted bridge architecture.

Managers in synergistic contexts like Uusimaa's broadcasting sector should invest in analytics to amplify brokerage. In rural clusters like Etelä-Savo, digital tools like VR can overcome barriers. In less synergistic contexts, such as hospitality in Uusimaa, hybrid networks combining digital and traditional ties can mitigate limitations. Policymakers should support digital innovation hubs and cross-regional collaborations, following models in Marche (Marinelli et al., 2024) and Espoo (Tukiainen et al., 2015), to enhance innovation potential across contexts.

5. Conclusion

This study examines how digital technology adoption shapes firms' innovation potential through positions in inter-organizational knowledge networks. By conceptualizing hyperlinks as digital traces of adoption, we captured firms' engagement with high-technology services, social media platforms, and cloud computing providers, linking these to Simmelian brokerage. Our findings demonstrate that DTA significantly enhances brokerage, enabling firms to bridge cohesive cliques and integrate diverse knowledge while preserving relational cohesion (Latora et al., 2013; Tasselli et al., 2025). This advances understanding of how technology fosters innovation not only via internal capabilities (Heavin & Power, 2018; Vial, 2019) but also through network structures that promote recombination and trust (Alberti et al., 2021).

However, the benefits of DTA are unevenly distributed. This study extends existing literature by demonstrating that the digital dividends of adoption are not universal but are strictly boundary-conditioned by sectoral knowledge intensity and regional infrastructure readiness. Sectoral analysis reveals knowledge-intensive industries such as broadcasting and consulting derive disproportionate gains, consistent with theories of absorptive capacity and weak-tie innovation (Shao et al., 2024). Conversely, sectors such as hospitality and food services exhibit weaker or negative effects, echoing findings that excess reliance on digital tools can deplete relational capital and hinder long-term innovation (Usai et al., 2021). Regional analysis underscores geography and infrastructure's role, with regions featuring robust ecosystems (often urban) enjoying stronger benefits, while remote or resource-scarce areas face constraints, aligning with uneven digital diffusion across geographies (Trinugroho et al., 2022). These results highlight DTA's contingent impact, moderated by contextual factors that determine whether it catalyzes innovation or adds coordination costs.

Theoretically, this research integrates digital technology adoption with network theory. Whereas prior work examined adoption outcomes within firms (Molinillo & Japutra, 2017; Shao et al., 2024), we show innovation potential emerges from relational positions in knowledge networks. We extend debates on network openness versus closure by demonstrating DTA supports hybrid configurations balancing cohesion and diversity. This enriches contingency theory, emphasizing external conditions' influence on innovation through a network perspective (Bertello et al., 2024; Gifford et al., 2021). Ultimately, these results challenge the linear assumptions of technology diffusion by proving that regional and sectoral contingencies can transform potential brokerage from a strategic asset into a latent liability in saturated or isolated contexts. Methodologically, hyperlink networks provide a novel, scalable proxy for adoption and inter-firm digital ties, facilitating analysis of large firm populations. This approach does not replace traditional surveys, but it is better suited for this paper's research questions. This method is not inherently better than traditional surveys. However, it is better suited for this paper's research questions. Abbasiharofteh et al. (2023) argue that a lack of large-scale relational data has limited research and hyperlinks network serves as a remedy for this problem in traditional empirical studies.

Practically, managers cannot assume uniform returns from technology adoption. In knowledge-intensive sectors, investing in cloud platforms, advanced ICT, and social media can amplify brokerage and innovation opportunities. In less knowledge-intensive or infrastructure-scarce contexts, combining DTA with traditional relational strategies may avoid coordination overload. Policymakers should address regional disparities through digital infrastructure and training investments, echoing digital innovation hubs in Italy's Marche region (Marinelli et al., 2024)

Despite these contributions, it is essential to recognize that innovation through technology adoption is a deeply complex and multifaceted process (Kruger & Steyn, 2024). In light of this complexity, several limitations should also be acknowledged.. While Simmelian brokerage identifies structural opportunities for knowledge recombination, realized innovation remains the result of complex creativity, constant R&D efforts, and human interaction that digital tools alone cannot replace (Usai et al., 2021). First, relying on static hyperlink networks from Finnish firms captures relational structures but overlooks dynamic DTA and brokerage evolution. Future longitudinal designs could examine changes during transitions (Brattström & Faems, 2020), complemented by qualitative approaches to uncover mechanisms shaping hyperlink formation and technology choices. Second, situated in digitally advanced Finland a top-ranked in the EU's DESI index the context isolates relational effects of DTA and limits generalizability to less mature economies. Cross-country comparisons would be needed to test sector-regional contingencies under varying digital development (Elfaki & Ahmed, 2024; Skare & Riberio Soriano, 2021). Third, hyperlink networks exclude firms without active websites or hyperlinks, tilting the sample toward digitally engaged organizations and potentially inflating brokerage for larger firms. Although we controlled for size and performed robustness checks, future studies could integrate survey-based or offline network data for broader coverage. Finally, the study omits human capital factors, such as employee skills or training, which shape the integration of digital adoptions (Cirillo et al., 2023).

In sum, this study shows that adopting digital technology enhances innovation potential by enabling brokerage positions in knowledge networks, conditioned by sectoral and regional contexts. Bridging DTA and network theory, it provides conceptual, empirical, and methodological insights into heterogeneous innovation outcomes, yielding actionable implications for managers and policymakers pursuing innovation-led growth.

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Appendix

Table 2 Regions in Finland

Region	Variation	Urban/Rural	Distance to Capital (km)	Main Industries
Ahvenanmaa	0.254662	Rural	~280	Tourism, shipping
Etelä-Karjala	-0.043816	Rural	~200	Forestry, manufacturing
Etelä-Pohjanmaa	0.105301	Rural	~350	Agriculture, food processing
Etelä-Savo	0.146848	Rural	~250	Forestry, tourism
Kainuu	-0.076377	Rural	~550	Forestry, mining
Kanta-Häme	0.213775	Mixed	~100	Agriculture, manufacturing
Keski-Pohjanmaa	0.099317	Rural	~400	Agriculture, energy
Keski-Suomi	-0.038629	Mixed	~270	Forestry, education
Kymenlaakso	0.008377	Mixed	~130	Logistics, manufacturing
Lappi	-0.299712	Rural	~800	Tourism, mining
Pirkanmaa	-0.103153	Urban	~160	Technology, manufacturing
Pohjanmaa	-0.151479	Mixed	~400	Energy, agriculture
Pohjois-Karjala	0.081865	Rural	~400	Forestry, bioeconomy
Pohjois-Pohjanmaa	-0.105243	Mixed	~550	Technology, forestry
Pohjois-Savo	0.015892	Mixed	~350	Agriculture, manufacturing
Päijät-Häme	0.030976	Mixed	~100	Manufacturing, food processing
Satakunta	-0.183072	Mixed	~200	Industry, agriculture
Uusimaa	0.073327	Urban	~0	Technology, services
Varsinais-Suomi	-0.028858	Urban	~150	Maritime, manufacturing