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Factors Influencing Industry 4.0 Adoption among Small and Medium Enterprises in Southeast Vietnam: An Integrated Technology-Organization-Environment-Resource-Based View-Diffusion of Innovation Framework

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ABSTRACT

The Industry 4.0 paradigm transforms how firms manufacture products, create value in digitalized markets, and sustain competitive advantage; nevertheless, the use of fourth industrial revolution technology among Vietnamese SMEs is confined. This work investigates the determinants of Industry 4.0 adoption for SMEs in Southeast Vietnam based on the integrated framework of the technology-organization-environment (TOE) model, the resource-based view (RBV), and the diffusion of innovation (DOI) theory. A sequential mixed-methods design was utilized. After refining and validating the measurement scales using qualitative inquiry and pilot studies, data were collected from 416 SME executives and analyzed with PLS-SEM. The findings suggest that external support plays the largest role in the Industry 4.0 adoption process, followed by support from top management, risk-taking culture, financial capability, human resource capability, competitive pressure, and perceived relative advantage. Conversely, technological complexity is detrimental to the technology adoption process. The culture of risk-taking acts as a mediator between organizational resources and technology adoption, while impacts of support from leadership and risk-taking culture are heightened in contexts of market turbulence. Theoretically, it contributes to the TOE literature by combining RBV and DOI perspectives, highlighting how organizational resources are converted into adoption outcomes through a risk-taking organisational culture. Practically, it provides policy-makers, industrial associations and SME managers with insights into promoting the accelerated digital transformation and stronger implementation of Industry 4.0.

Keywords: Industry 4.0, Small and Medium Enterprises, Technology Adoption, Technology–Organization–Environment Framework, Resource-Based View, Vietnam

JEL Classifications: O32, O33, M15

1. INTRODUCTION

Firms have increasingly recognized that sources of competitive advantage are shifting toward data-driven decision making, digital connectivity, intelligent automation, and cyber-physical systems. These technologies have become strategic assets that enhance operational efficiency, agility, and long-term competitiveness. But there is a discernible gap between countries' ambitions for digital transformation and the technological implementation actually achieved by enterprises. Despite widespread government efforts to promote digitalisation, uptake of advanced digital technologies (cloud computing, big data analytics, artificial intelligence) in Vietnamese firms is relatively low (Cirera et al., 2021). Since SMEs comprise more than 97% of active enterprises in Vietnam, they present both a barrier to, and opportunity for, achieving the goals of the country's digital transformation strategy (Cirera et al., 2021).

Despite the substantial operational and competitive advantages accompanying Industry 4.0 technologies, SMEs' uptake remains between moderate and low (Wong and Kee, 2022) in many emerging economies. What explains this phenomenon? Digital technologies offer substantial opportunities for innovation, firm growth, and competitive performance. However, small and medium enterprises in emerging markets tend to trail their larger competitors, largely due to shortcomings in resources, organizational capabilities and external support conditions (Indiani et al., 2025). This phenomenon is particularly evident in Southeast Vietnam and other highly industrialized areas, which are becoming more strictly integrated on a global economic scale, with growing competitive pressure from foreign-invested firms. While prior studies have correctly highlighted the associations of technological, organizational, and environmental factors with Industry 4.0 adoption (e.g., Grooss et al., 2022; Le et al., 2023), organizations' ability to transform resources into technological outcomes by way of technology adoption have not been deeply examined and less attention is given to internal cultural composition, e.g. risk-taking culture.

According to Anshari and Almunawar (2022), "the successful adoption of Industry 4.0 among SMEs is not only a question of being technologically prepared but also of the availability of a supportive digital ecosystem to facilitate collaborative, and open innovation". Despite the many opportunities provided by Industry 4.0, SMEs continue to face significant challenges during the initial stages of digital transformation as a result of technological, organizational and environmental issues (Ghobakhloo et al., 2022).

An overview of the literature reveals three key gaps to address. The first is that much research studies either a driver or fear of technology adoption, so explanations for adoption are very fragmented and rarely has "more complete" -technological, organizational, environmental and resource-based- understanding in mind. The second is that most empirical evidence has been derived from developed countries or pragmatically referred to contexts outside of Vietnam where pronounced regional variations may influence the technology adoption. And the third is that few studies have employed a comprehensive mixed-methods approach that are comprehensive in their systematic literature reviews, scale development, qualitative exploration, and large-scale quantitative.

Past research finds that SMEs struggle with many areas of digital transformation: including finances, lack of personnel, low organizational readiness, complexity of technology, and lack of external support. However, SMEs are also characterized by flexibility, simplicity of structure, and centralization which may allow for faster responses to technology opportunities, as long as organizations are adequately capable and favorable conditions exist.

Even though the opportunities associated with Industry 4.0 technologies for productivity, innovation and competitiveness are great, SMEs keep facing issues like leadership commitment, digital infrastructure, and workforce readiness, which affects their ability to adapt and felt fit in a more digitalized economy (Techanamurthy et al., 2025). Taking the ideas of these challenges and of the research gaps observed in the literature, this study seeks the achievement of three objectives. First, it develops and tests an integrated framework to explain Industry 4.0 technology adoption among SMEs in Southeast Vietnam. Second, it examines the mediating effect of risk-taking culture in the relationship between organizational resources and their outcomes in terms of technology adoption. Third, it investigates the moderating effect of market turbulences in the linkages between leadership support, organizational culture and Industry 4.0 adoption.

To achieve these aims, this study is motivated by two research questions: what factors and mechanisms inhibit or promote the adoption of Industry 4.0 technologies by SMEs in Southeast Vietnam? What implications can be drawn for stakeholders such as SME managers, industry associations, policymakers, and local authorities to support the adoption of technologies of Industry 4.0?

2. LITERATURE REVIEW

2.1. Theoretical Background

This research is built on three touchstones: the technology–organization–environment (TOE) framework, diffusion of innovation (DOI) theory and resource-based view (RBV). Together, the three perspectives allow for a full exploration of the dimensions of organizational technology adoption in terms of technology attributes, internal organizational factors and external environmental factors.

Although originating in the socio-economic literature with Tornatzky et al. (1990), the TOE framework considers the contextual situation surrounding the adoption of the innovation at the organizational level within three interrelated contexts: Technological, organizational, and environmental. The technological context comprises both existing and emerging technologies that are pertinent to the firm; the organizational context includes internal characteristics such as managerial structures and communication procedures as well as the availability of organizational resources. Finally, the environmental context includes the specific industry situations, competitor pressures, pressure from regulatory bodies, and dealings with other stakeholders outside the firm (Tornatzky et al., 1990). From a TOE perspective, technology adoption in organizations does not depend solely on the technology itself but the three factor influence of technology, organization and environment.

To complement the TOE framework in explaining adoption behavior, this study incorporates diffusion of innovation (DOI) theory (Rogers, 2003). DOI complements TOE by explaining how innovations diffuse across organizations, telling us how, within social systems, an innovation spreads, as well as why one innovation is likely to be adopted more readily than another. DOI identifies a number of characteristics of an innovation that might affect behavior. Relative advantage and complexity are key amongst other things. Relative advantage refers to the degree to which an innovation is perceived as being better than the idea it supersedes or substitutes for. Complexity refers to the degree to which an innovation is seen as difficult to use, understand or learn. (The extent to which an innovation is perceived as difficult to understand, learn or use) According to Rogers' DOI theory, where an innovation is perceived to have a relative advantage and a lower level of complexity, it is more likely to be adopted by prospective users.

This study also relies on the resource-based view (RBV) of Barney (1991) that emphasises the key role of internal organisational resources it plays in gaining competitive advantage. RBV states that sustained superior performance depends on resources that are valuable, rare, difficult to imitate and non-substitutable as per Barney (1991). In this view, financial and human resources are important organisational assets that can condition the ability of a firm to acquire, implement, and use new technologies. For this reason, firms with superior resource endowments are generally more capable of technological innovation and projects of organisational transformation. In addition, advanced technologies increasingly enable more intuitive human–computer interactions by using visual behavior and intelligent computational techniques to interpret users' implicit intentions (Madhusanka et al., 2024).

While TOE, DOI and RBV perspectives add insights into the topic of technological adoption in organisations, none of these perspectives alone offers a comprehensive explanation of Industry 4.0 adoption. The TOE framework emphasizes the technological, organizational, and environmental contexts, organisation, and environment contexts of adoption decisions but does not give consideration to firms' strategic resource endowments. DOI theory centres mainly on how potential adopters assess the characteristics of an innovation relates but does not give attention to organisational capabilities and availability of resources. In contrast, RBV emphasizes the role of internal resources in informing strategic action and creating competitive advantage, but provides less insight on external environmental forces and technology-related specificities. Pairing TOE and DOI with RBV results in a comprehensive perspective on Industry 4.0 adoption that is sensitive to environmental conditions, technological impressions, and organizational resources in a single framework. This perspective seems particularly appropriate for SMEs' adoption decisions which are frequently informed at the same time by environmental attributes as well as resource limitations.

In general, previous theoretical and empirical studies indicate that Industry 4.0 adoption is influenced by a combination of technological, organizational, environmental, and resource-related factors, thereby supporting the use of an integrated theoretical framework to explain adoption behavior.

2.2. Synthesis of Theoretical Foundations and Prior Research

Table 1 summarizes the key studies underpinning the development of the research framework.

Existing research has shown that Industry 4.0 adoption is contingent upon a range of technological, organisational and environmental factors. Indeed, Grooss et al. (2022) summarizing the SME literature say that for successful Industry 4.0 implementation, it is necessary to address factors across all three TOE dimensions. Consequently, we make use of the TOE framework as the primary lens for exploring Industry 4.0 adoption amongst SMEs.

2.3. Hypotheses and Model Development

2.3.1. Organizational resources and industry 4.0 adoption

According to the resource-based view (RBV), organizational resources constitute a key source of competitive advantage and provide critical support for technological innovation and organizational change. For Industry 4.0, then human resource capability and financial capability are particularly pertinent as cutting-edge technology will not yield value added unless firms have workers who are made capable to relate to, run and sustain and improve technological systems (Masood and Sonntag, 2020; Mittal et al., 2018; Mustafa et al., 2024). Similarly, investing in Industry 4.0 technologies requires substantial investments not only in technological infrastructure but also in employee training, process redesign, maintenance, and system integration (Masood and Sonntag, 2020; Mittal et al., 2018; Shahzad et al., 2023; Tamvada et al., 2022).

Similarly, firms with greater human resource capability are likely to find it easier to absorb technologies, carry out digital transformation projects, and get used to new technological needs. Firms with greater financial capability, on the other hand, are likely to be better able to afford the costs and risk of absorbing Industry 4.0. Both these factors are expected to support Industry 4.0 adoption among SMEs.

Resources may contribute to creating a risk-taking culture. Firms that have sufficient financial reserves, can afford to have confidence in the capabilities of employees, are more likely to encourage experimentation, learn to tolerate uncertainty and pursue technological experimentations. Human resource capability/skills and financial capability are thus predicted to have a positive relationship with the creation of a risk-taking culture. Following the lines of RBV, we expect that organizational resources create value not only when being directly deployed but also when forming organizational capabilities and orientations that are conducive to developing innovation and a propensity to technological changes. Therefore, the following hypotheses are proposed:

H_1: Human resource capability has a positive effect on Industry 4.0 technology adoption among SMEs

H_2: Financial capability has a positive effect on Industry 4.0 technology adoption among SMEs

H_4: Human resource capability positively influences the development of a risk-taking culture within SMEs

H_5: Financial capability positively influences the development of a risk-taking culture within SMEs.

2.3.2. Organizational factors and industry 4.0 adoption

Under the organizational dimension of the TOE framework, top management support and Risk-taking culture have all been found to be influential on Industry 4.0 adoption. Decision in SMEs is usually taken primarily by the owner or the top management team. If leaders communicate a technological vision, provide dedicated budgets, have technology's associated objectives in the performance appraisal systems, and proactively build external partnerships, technological innovation would be legitimized (Grooss et al., 2022; Jayashree et al., 2022; Shahzad et al., 2023).

Typically, firms implementing Industry 4.0 initiatives will face uncertain, experimental environments that require organizational learning, and therefore also need a culture that encourages employees to take risks, be willing to explore, learn to fail, and adapt to changes. Grooss et al. (2022); Hock-Doepgen et al. (2021); Masood and Sonntag (2020) found that while top management support is important, it is risk-taking culture that prepared organizations for successful implementation. Accordingly, the following hypotheses are proposed:

H_3: Risk-taking culture has a positive effect on Industry 4.0 technology adoption among SMEs

H_6: Top management support has a positive effect on Industry 4.0 technology adoption among SMEs.

2.3.3. Environmental factors and industry 4.0 adoption

Within the environmental dimension of the TOE framework, additional elements include external support and competition pressure. External support includes the availability of government support policies, technology vendors, technical consulting services, industry associations, cooperative networks, and the wider institutional environment, that is, something that would support the implementation of that technology (Jayashree et al., 2022; Masood and Sonntag, 2020; Shahzad et al., 2023). Such support reduces uncertainty, decreases the cost of implementation and facilitates the adoption of the new technology.

Competitive pressure refers to the risk of losing customers, market share, or supply-chain participation if firms do not digitalize or fall behind developments in their markets (Jayashree et al., 2022; Shahzad et al., 2023). Both types of incentives represent elements of a push–pull mechanism, where support facilitating adoption is pulling firms toward technology while competitive pressure increases the cost of waiting for firms. Therefore, the following hypotheses are proposed:

H_7: External support has a positive effect on Industry 4.0 technology adoption among SMEs

H_8: Competitive pressure has a positive effect on Industry 4.0 technology adoption among SMEs.

2.3.4. Technological factors and industry 4.0 adoption

Based on diffusion of innovation (DOI) theory, two characteristics of technology dealing with DOI adoption are examined; relative advantage and complexity. The first concept refers to the degree in which a technology is believed to improve productivity, product quality, service quality, customization, operational efficiency, cost reductions, and market competitiveness (Jayashree et al., 2022; Masood and Sonntag, 2020; Shahzad et al., 2023) where complexity refers to the degree which the technology is perceived to be difficult to learn, to integrate, to operate, to manage, and to predict a total cost for ownership (Masood and Sonntag, 2020; Mittal et al., 2018; Shahzad et al., 2023; Tamvada et al., 2022).

As a corollary of DOI theory, innovations perceived to be beneficial will be adopted more than those perceived to be hard to understand or to use, suggesting that relative advantage will encourage Industry 4.0 adoption but complexity will impede adoption decisions. Accordingly, the following hypotheses are proposed:

H_9: Complexity has a negative effect on Industry 4.0 technology adoption among SMEs

H_{10}: Relative advantage has a positive effect on Industry 4.0 technology adoption among SMEs.

2.3.5. The moderating role of market turbulence

A useful addition made by this study is the inclusion of market turbulence as a contextual moderator. Market turbulence indicates the extent to which customer preferences, technological standards, competitive strategies, and market conditions change over time. This facet appears to be less important for firms operating in relatively stable market conditions where the cost of delaying technology investments does not greatly impact their firms' short-term viability (Lawrence and Lorsch, 1969). In relatively fast-paced and turbulent environments that demonstrate rapid technological obsolescence, changing customer demands, shifting competitive dynamics, and evolving supply-chain requirements, organizational capabilities become comparatively important (Hock-Doepgen et al., 2021; Jaworski and Kohli, 1993; Jayashree et al., 2022).

Under these conditions, firms with committed leaders and a culture of experimentation generally tend to respond to environmental uncertainty and technological change better. Hence, market turbulence is expected to strengthen the effect of top management support and risk-taking culture on adoption of Industry 4.0. Accordingly, the following hypotheses are proposed:

H_{11}: Market turbulence positively moderates the relationship between top management support and Industry 4.0 technology adoption, such that the relationship becomes stronger under higher levels of market turbulence

H_{12}: Market turbulence positively moderates the relationship between risk-taking culture and Industry 4.0 technology adoption, such that the relationship becomes stronger under higher levels of market turbulence.

The study tests twelve hypotheses involving direct, mediating, and moderating effects. In addition, firm size, firm age, and industry characteristics were included as control variables in the structural model.

By integrating the TOE, DOI and RBV into a framework we posit the adoption of Industry 4.0 as a function of interaction among organizational resources, technological perceptions, environmental conditions, and organizational culture. This integrative view extends previous adoption studies by situating risk-taking culture as a mediating mechanism and market turbulence as a contextual boundary condition.

The proposed conceptual model, presented in Figure 1, integrates the TOE, DOI, and RBV perspectives and specifies the hypothesized relationships examined in this study.

3. METHODOLOGY

3.1. Research Design

To enhance the contextual relevance of the measurement device as well as the methodological rigor of the proposed framework, this study opted for a sequential mixed-methods research design. This methodology is appropriate when well-established theoretical constructs are studied in a new research context where adaptation of measurement scales is required through some degree of empirical validation. In this way, the research was conducted in a stepwise manner through five consecutive stages: (1) literature review and initial scale development, (2) exploratory qualitative research, (3) pilot quantitative testing, (4) qualitative confirmation of results and questionnaire refinement, and (5) a large-scale quantitative testing of the proposed model.

The first phase was concerned with literature review on Industry 4.0 adoption, digitalization, the TOE framework, DOI theory, and RBV. Based on existing validated scales an initial set of items for the survey were developed.

During the second stage, exploratory qualitative research was conducted using in-depth interviews with 15 experts, including academics, managers of SMEs, digital transformation consultants and industry experts, to ascertain how appropriate, clear, and contextually relevant the proposed measurement items were for SMEs operating in southeast Vietnam. Issues that were considered particularly relevant to the local context included: competition from foreign-invested enterprises, industrial park development, export-related technical requirements, and accessing external support resources.

The third stage featured a pilot survey of 125 SMEs in order to examine the reliability and validity of the measurement scales prior to the main study. Measurement scales were assessed using Cronbach's alpha, outer loading analysis, convergent validity, and discriminant validity criteria, yielding satisfactory psychometric properties, thus retaining 10 latent constructs represented by 50 observed indicators for further examination.

In the fourth stage, a follow-up qualitative assessment was conducted with some of the experts to confirm the wording and content of the questionnaire and check that the theoretical constructs and potential measurement items were aligned. This feedback was incorporated into the final survey.

The fifth phase included a large survey that quantitatively examined the hypotheses and relationships incorporated in the study. The research model was assessed through using partial least squares structural equation modeling (PLS-SEM)—a flexible approach of analysis appropriate for predictive research models involving mediating and moderating relationships.

3.2. Measurement Instrument

The measurement instrument comprised ten constructs measured using five-point Likert scales. The measurement items were adapted from prior studies and refined through expert interviews, pilot testing, and follow-up qualitative assessment to ensure their relevance to the SME context in Southeast Vietnam. The final measurement items and their respective sources are presented in Table 2.

The final measurement items and their sources are presented in Table 2.

3.3. Sampling and Data Collection

In the official phase, the survey targeted key informants at SMEs: Business owners, CEOs, board members, or senior managers. Key informants were selected because decisions on investments in technologies, resource commitments, evaluations of the competitor environment, and risk perceptions require broad knowledge of the firm which they rank-and-file may lack. The questionnaire was divided into three parts: Company info, the main measurement scales, and questions to extract basic info from respondents. All the observed items used a 5-point Likert scale. Firm size (CTV1), firm age (CTV2), and industry characteristics (CTV3) were coded as firm-level control variables and included in the PLS-SEM analysis. The survey was conducted pro bono in person in January 2026-May 2026.

A total of 450 questionnaires were distributed and collected, of which 34 were discarded due to missing data or poor response quality; 416 valid responses remained, yielding a 92.4% effective response rate. Sample statistics indicate a relatively young leadership: 97.1% of respondents were under 40 years old; 61.5% had 5-10 years of management experience; and 82.0% held at least a bachelor's degree. The industry distribution in the survey is quite diverse: Trade and services (28.1%), logistics and transportation (15.1%), education and training (16.1%), tourism (11.3%), agriculture (7.0%), agricultural processing (6.0%), mechanical manufacturing (5.0%), healthcare (4.1%), and textiles and footwear (3.1%). This diversity suggests the model can generalize well within the study region. The demographic and firm characteristics of the final sample are reported in Table 3.

The study initially operationalized ten constructs with five observed items each: Industry 4.0 technology adoption (5 items), relative advantage (5 items), complexity (5 items), top management support (5 items), risk-taking culture (5 items), external support (5 items), competitive pressure (5 items), financial capability (5 items), human resource capability (5 items), and market turbulence (5 items). The observed items were developed from prior studies and refined through multiple qualitative rounds. In addition, the author and the experts discussed and added context-specific items for the Southeast region relating to pressure from foreign direct investment (FDI), access to preferential financing concentrated in Ho Chi Minh City, and changes in technical standards across global supply chains. This addition is fully justifiable because recent reviews consistently emphasize the need to localize measurement scales when studying SMEs in emerging economies.

The study employed PLS-SEM in SmartPLS 4 to assess both the measurement model and the structural model. PLS-SEM was selected for three reasons: (1) the study is oriented more toward explaining and predicting the level of technology adoption than toward testing a fully confirmatory theory; (2) the model is relatively complex, with direct, mediating, moderating, and control relationships; and (3) compared with alternative methods, PLS-SEM is more suitable for firm-level data because it imposes less restrictive assumptions regarding normal data distribution. The evaluation criteria for the measurement and structural models followed widely used recommendations: outer loadings of approximately 0.708 or higher; Cronbach's alpha and composite reliability above 0.70 (Hair et al., 2009, 2019; Nunnally and Bernstein, 1994), AVE above 0.50 (Fornell and Larcker, 1981; Hock and Ringle, 2010), and HTMT below 0.85 or 0.90, depending on the conceptual proximity of the constructs (Henseler et al., 2015). Bootstrapping with 5,000 resamples was used to test statistical significance, and predictive power was assessed using PLSpredict and Q^2predict (Hair et al., 2019).

The design of this research procedure helps address a common weakness in technology studies on SMEs: The direct adoption of original theory-based scales without verifying their fit to the research context.

3.4. Assessment of Common Method Bias

Considering that data were all collected from a single respondent in each firm via a self-administered questionnaire, common method bias (CMB) was investigated. Following Kock (2015), a full collinearity assessment was performed. VIF values for all latent constructs were found to be well below the 3.3 threshold thus indicating that common method bias was not a potential threat to the validity of our findings.

To further corroborate this result, Harman's single-factor test was conducted. An unrotated exploratory factor analysis yielded less than 50% of total variance accounted for by the first factor, indicating that no one factor explained the majority of covariance among the measurement items. Thus, the results provide further support for the conclusion that common method bias was not a serious concern in this study.

4. RESULTS

Preliminary descriptive analysis indicates that SME managers in Southeast Vietnam generally have favorable perceptions towards both technological and market-related pressures. For the 50 original measurement items, mean scores ranged from 3.53 to 3.98 suggesting general agreement. Of the constructs, market turbulence received some of the highest mean scores (3.83-3.97) and lowest standard deviations (0.624-0.649) suggesting strong agreement among respondents on the prevalence of dynamic market conditions, accelerating technological change and increasingly unpredictable competitive behaviour. These suggest partial support for the inclusion of market turbulence as a moderating variable in the proposed research model.

The measurement model was then assessed to check reliability and validity. During the initial evaluation four indicators (CT5, HT2, PT3, and TC5) that did not meet the recommended outer loading threshold were discarded. The final measurement model retained a total of 46 observed indicators. All other constructs demonstrated acceptable psychometric properties with Cronbach's alpha scores ranging from 0.841 to 0.886, composite reliability (rho_c) values between 0.894 and 0.916, and average variance extracted (AVE) scores of between 0.641 and 0.697. These scores confirm adequate internal consistency and convergent validity of the measurement scales, indicating that the scales closely captured their respective latent constructs and explained a large proportion of the variance in indicators.

4.1. Construct Reliability and Convergent Validity Results

The results of the assessment of construct reliability and convergent validity, including Cronbach's alpha, composite reliability, and average variance extracted (AVE), are presented in Table 4.

Discriminant validity was also established. The Fornell–Larcker matrix showed that the square root of the AVE for each construct exceeded its correlations with the remaining constructs. The HTMT matrix was below the acceptable threshold. Although constructs such as external support, competitive pressure, and market turbulence are semantically close, satisfying the discriminant validity criteria indicates that respondents nevertheless distinguished these concepts in their managerial perceptions.

4.2. Assessment of Discriminant Validity

The results of the heterotrait–monotrait ratio (HTMT) assessment for establishing discriminant validity are presented in Table 5.

In the structural model, all hypothesized paths were statistically significant. Among the direct predictors of the dependent variable, external support had the largest coefficient among the substantive predictors ($\beta = 0.168$; $P < 0.001$), followed by top management support ($\beta = 0.132$; $P < 0.001$), risk-taking culture ($\beta = 0.124$; $P < 0.001$), relative advantage ($\beta = 0.099$; $P < 0.001$), financial capability ($\beta = 0.097$; $P < 0.001$), human resource capability ($\beta = 0.090$; $P = 0.013$), and competitive pressure ($\beta = 0.088$; $P = 0.006$). Complexity had a significant negative effect ($\beta = -0.104$; $P < 0.001$), as expected theoretically. At the same time, human resource capability ($\beta = 0.381$; $P < 0.001$) and financial capability ($\beta = 0.358$; $P < 0.001$) both significantly strengthened risk-taking culture.

4.3. Results of Hypothesis Testing

The results of the hypothesis testing, including the estimated path coefficients, t-values, p-values, and corresponding decisions, are presented in Table 6.

When indirect effects through risk-taking culture were added, the total effect of financial capability was approximately 0.142, and that of human resource capability was about 0.137. This suggests that resources in themselves, whether human or financial, are not sufficient. What matters is whether the firm can convert those resources into a culture that is willing to experiment with the new. Conceptually, this distinguishes the simple assumption that "if firms have money and people, digital transformation will follow" from the deeper view that resources create value only when they are organized into innovative attitudes and behaviors. The final measurement model, after removing the four indicators that did not meet the recommended outer-loading threshold, is presented in Figure 2.

In terms of explanatory power, the Industry 4.0 adoption construct reached $R^2 = 0.833$ and adjusted $R^2 = 0.827$, while risk-taking

Table 1: The summarizes related studies in this field

Sources	Context	Model	Method	Key findings	Limitations
(Tornatzky et al., 1990)	Business and technological innovation	TOE	Concept	Technology, organization, and environment are the three core contexts of innovation acceptance.	
(Barney, 1991)	Strategic theory	RBV	Theory	Valuable, rare, and difficult-to-imitate resources determine competitive advantage.	
(Rogers, 2003)	Diffusion of innovation	DOI	Theory	Relative advantage and complexity directly influence the acceptance of innovation.	
(Mittal et al., 2018)	SMEs in manufacturing	Maturity model review	Overview	SMEs need a separate roadmap due to differences in resources and readiness levels.	There is no quantitative analysis to compare the differences between the models.
(Masood and Sonntag, 2020)	SMEs	Adoption challenges and benefits	Overview/ Survey	The main benefits are efficiency, flexibility, and cost; the main barriers are finance and knowledge.	Focus only on one developed country. Do not construct a causal relationship model.
(Ghobakhloo et al., 2022)	SMEs in manufacturing	SLR+ roadmap	System overview	Barriers and drivers should be viewed as a transformational construct, not as separate variables.	Quantitative analysis has not yet been conducted to identify the main barriers to developing appropriate solutions.
(Zamani, 2022)	SMEs	SLR	System overview	Research on technology in SMEs needs to emphasize the dynamic process and the interaction between internal conditions and the environment.	There have been no field studies to prove the relationship between these factors.
(Intalar et al., 2024)	Thai SMEs	RBV	Quantitative survey	Awareness of Industry 4.0, leadership support, financial autonomy, human resource development strategies, and external support all have a positive and significant impact on the application of Industry 4.0.	The differences between industries have not yet been considered.
(Shahzad et al., 2023)	Malaysian SMEs	TOE, DOI	Quantitative survey.	Relative advantage, compatibility, organizational readiness, senior management support, competitive pressure, and government regulations all have a positive and significant impact on the adoption of Industry 4.0.	Many other organizational factors haven't been considered yet.
(Fernando et al., 2023)	Indonesian SMEs	TOE and institutional theory		There are five main policy barriers—investment risk, lack of security, lack of expertise, and lack of incentives—that will hinder the adoption of technology.	Focusing solely on one developed country. No differentiation across industries.
(Tamvada et al., 2022)	Indian SMEs	TAM, TOE	Fuzzy-analytic hierarchy process	Financial risks and technological risks are the biggest obstacles hindering SMEs.	The context in India is different from that in Vietnam. Many other organizational factors haven't been considered yet.
(Grooss et al., 2022)	SMEs (international)	TOE	System overview	Key barriers: finance, knowledge, and resistance to change. A suitable strategy is needed for SMEs.	This is a review paper, without primary experimental data.
(Jayashree et al., 2022)	Malaysian SMEs	TOE and DOI	SEM	The innovative nature of the technology has a positive impact on the application of Industry 4.0 and the goal of sustainability	Focusing on the connection to sustainability may overlook other organizational factors.
(Hock-Doepgen et al., 2021)	SMEs are mostly from Germany.	Quantitative survey	Dynamic capacity theory	Knowledge management capabilities positively influence the willingness to take risks for innovation.	Instead of directly researching and applying Industry 4.0, the focus is on innovating business models.

culture reached $R^2 = 0.367$ and adjusted $R^2 = 0.364$. These values indicate that the set of independent variables, together with the study context, captured and explained a substantial share of technology adoption behavior. In other words, within the scope of this study, Industry 4.0 adoption among SMEs was explained by a relatively coherent integrated model.

4.4. Explanatory Power and Predictive Assessment Results

The results of the explanatory and predictive assessment, including R^2, adjusted R^2, Q^2predict, RMSE, and MAE values, are summarized in Table 7.

With respect to effect size, the f^2 values show that human resource capability and financial capability exerted positive effects on risk-taking culture, with effect sizes of 0.205 and 0.164, respectively. For the dependent variable, most direct effects were small to moderate in magnitude. This is consistent with the nature of

Table 2: Technology adoption scale

Item	Description	Adapted from source
Application of industry 4.0 technology (UD)		
UD1	Industry 4.0 technology has been deeply integrated into our operational processes (e.g., production, inventory, delivery, supply chain)	(Jayashree et al., 2022)
UD2	We use Industry 4.0 tools (e.g., data analytics, AI) to drive innovation and develop new products/services	(Jayashree et al., 2022)
UD3	Our core business processes are now managed and optimized on an Industry 4.0 platform	(Shahzad et al., 2023)
UD4	Critical operational decisions in our company are now made using real-time data collection and analysis	(Shahzad et al., 2023)
UD5	The level of automation in our production (or service) operations has significantly increased thanks to Industry 4.0 technology	(Masood and Sonntag, 2020)
Relative advantage (LT)		
LT1	Industry 4.0 allows us to quickly customize products/services to meet customer requirements	(Amin et al., 2024)
LT2	We expect Industry 4.0 to significantly reduce defect rates and increase customer satisfaction	(Masood and Sonntag, 2020)
LT3	We expect Industry 4.0 to reduce specific costs (e.g., raw materials, labor per unit)	(Shahzad et al., 2023)
LT4	Adopting Industry 4.0 is a key factor in helping us access new customer segments	(Shahzad et al., 2023)
LT5	Adopting Industry 4.0 will enhance our ability to meet the strict requirements of major export markets	Developed by research.
Financial capacity (TC)		
TC1	We have the capacity to invest in Industry 4.0 technology without negatively impacting our daily operating cash flow	(Mittal et al., 2018)
TC2	The current conditions (e.g., interest rates, collateral) for borrowing technology investment capital from banks are major barriers for us	(Masood and Sonntag, 2020)
TC3	Our financial structure is robust enough to pursue technology projects with long-term payback periods (over 3-5 years)	(Masood and Sonntag, 2020)
TC4	We have a policy of allocating a reserve budget for replacing technologies when they become obsolete	(Tamvada et al., 2022)
TC5	Our company can access preferential loans and venture capital concentrated in Ho Chi Minh City	Developed by research.
Human resource capability (NL)		
NL1	We are confident in our ability to train and develop our workforce to meet Industry 4.0 requirements	(Mustafa et al., 2024)
NL2	Our mid-level management team has the capability to lead digital transformation projects in their departments	(Mustafa et al., 2024)
NL3	Our corporate culture of teamwork and cross-department collaboration supports complex technology projects	(Mustafa et al., 2024)
NL4	We can quickly form cross-functional project teams to implement new technology initiatives	(Mustafa et al., 2024)
NL5	Our company can compete for and retain technical talent despite the attraction of large FDI firms	Developed by research.
Market turbulence (BD)		
BD1	The technology we currently use is at risk of becoming obsolete within the next 2-3 years	(Jayashree et al., 2022)
BD2	Customer preferences and needs change very rapidly in our market.	(Jayashree et al., 2022)
BD3	We are often surprised by price, product, or strategy moves of our main competitors	(Hock-Doepgen et al., 2021)
BD4	The rate at which products/services become outdated in our industry is very high	(Hock-Doepgen et al., 2021)
BD5	Requirements and standards from global supply chains that affect us change frequently	Developed by research.
Complexity (PT)		
PT1	We are concerned that integrating new Industry 4.0 technologies will cause serious disruption to our current production and business operations	(Tamvada et al., 2022)
PT2	Finding and recruiting personnel with sufficient skills to operate Industry 4.0 technologies is a major challenge for us	(Shahzad et al., 2023)
PT3	It is very difficult to accurately forecast the total cost of ownership (TCO) of Industry 4.0 technologies, including both hidden and maintenance costs	(Masood and Sonntag, 2020)
PT4	We find that a significant amount of training and learning time is needed for employees to become proficient in using Industry 4.0 technologies	(Masood and Sonntag, 2020)
PT5	High labor turnover rates in the region make it difficult to train employees and transfer technological knowledge to new personnel	Developed by research.
Top Management support (LD)		
LD1	The leadership team regularly communicates the strategic importance of applying Industry 4.0 to all employees	(Shahzad et al., 2023)
LD2	The leadership team allocates a separate and protected budget for Industry 4.0 projects	(Shahzad et al., 2023)
LD3	Goals related to Industry 4.0 application are incorporated into the management's performance evaluation system (KPIs)	(Shahzad et al., 2023)
LD4	The leadership team has a clear and compelling vision of how Industry 4.0 will shape the company's future	(Jayashree et al., 2022)
LD5	Our leadership team proactively seeks collaborative technology projects with partners in the high-tech zone	Developed by research.
Risk-taking culture		
RR1	Our company is willing to invest in new technology projects even when the return on investment (ROI) is uncertain.	(Hock-Doepgen et al., 2021)
RR2	When a pilot technology project fails to meet its objectives, the project team is encouraged to share lessons learned without fear of reprimand	(Grooss et al., 2022)
RR3	Our company has a formal process or budget for testing new ideas or technologies	(Grooss et al., 2022)

(Contd...)

Table 2: ***(Continued)***

Item	Description	Adapted from source
RR4	We accept that Industry 4.0 technology projects may require more time to implement and pay back than conventional projects	(Masood and Sonntag, 2020)
RR5	We are prepared to rapidly change production processes to meet new technical requirements from international customers	Developed by research.
External support		
HT1	We found information on government technology support policies to be clear and easy to find	(Shahzad et al., 2023)
HT2	The application process for government incentives/support for technology application is simple and feasible for SMEs	(Shahzad et al., 2023)
HT3	We easily found reputable and capable local technology providers for technical support	(Jayashree et al., 2022)
HT4	Industry associations provide useful and practical consulting or networking programs for the application of Industry 4.0	(Jayashree et al., 2022)
HT5	Specific incentive policies in key economic zones are clear and accessible	Developed by research.
Competitive pressure		
CT1	The application of Industry 4.0 technologies by competitors is creating direct pressure on our market share	(Shahzad et al., 2023)
CT2	We face the risk of losing important customers if we do not keep up with the pace of technological innovation of our competitors	(Shahzad et al., 2023)
CT3	Our largest customers require us to integrate digital systems in order to continue collaborating	(Jayashree et al., 2022)
CT4	Failure to adopt digital technology will reduce the effectiveness of collaboration and risk being excluded from the supply chain of major partners	(Jayashree et al., 2022)
CT5	We feel competitive pressure from FDI businesses in the same industrial park	Developed by research

Table 3: Descriptive statistics table showing values by survey sample characteristics

Sample characteristics	Quantity	Percent	Valid percent	Cumulative percent
Sex				
Male	262	63.0	63.0	63.0
Female	154	37.0	37.0	100.0
Total	416	100.0	100.0	
Age				
Ages 18-30	133	32.0	32.0	32.0
Ages 30 to under 40	271	65.1	65.1	97.1
Ages 40 to under 50	12	2.9	2.9	100.0
Total	416	100.0	100.0	
Number of years of experience				
Under 5 years	133	32.0	32.0	32.0
From 5-10 years	256	61.5	61.5	93.5
Over 10 years	27	6.5	6.5	100.0
Total	416	100.0	100.0	
Education				
College	75	18.0	18.0	18.0
Bachelor	296	71.2	71.2	89.2
Master	45	10.8	10.8	100.0
Total	416	100.0	100.0	

(Source: Compiled by the author)

technology decisions in SMEs, where adoption is the cumulative result of multiple conditions operating simultaneously rather than the product of a single dominant driver. The managerial implication is clear: no single "lever" can substitute for coordinated reform.

Finally, out-of-sample predictive assessment showed that the Q^2 predict value for Industry 4.0 adoption was 0.720, indicating very strong predictive power. The Q^2 predict value for risk-taking culture was 0.359, which indicates a moderate level of predictive power. Overall, the positive Q^2 values and favorable predictive strength suggest that the model is not only useful for *ex post* explanation but also has predictive value for firms' technology adoption behavior.

5. DISCUSSION

The results indicate that Industry 4.0 adoption by SMEs is a complex combination of organizational resources and capabilities, technological perceptions and uptake, environmental conditions and legitimacy, and organisational culture. In line with the integrated TOE-RBV-DOI framework, technology adoption is more than a choice of technology, but rather an integrative organisational process which requires alignment of technological, organisational and environmental (TOE) factors (Tornatzky et al., 1990).

The external ecosystem is the most significant predictor of adoption of Industry 4.0 overall. This means that an external ecosystem is very important in facilitating the digital transformation of small and medium enterprises (SMEs) through a lack of resources; as a result of resource limitations, SMEs will often depend on external entities (e.g. government policy, industry association, software vendor; partners) to reduce uncertainty and reduce barriers to adoption. This finding supports the environmental dimension in the technology-organisation-environment (TOE) framework and supports previous studies that show the importance of support from the ecosystem in accelerating the implementation of Industry 4.0 (Shahzad et al., 2023; Ghobakhloo et al., 2022).

The findings also affirm that firms' financial capacity and firm human resource capability are directly related to adoption of Industry 4.0, both by exhibiting a consistently positive influence on adoption directly as well as indirectly through risk-taking culture. Thus, our findings indicate that firm resources on their own do not contribute significantly to digital transformation unless they find a way to translate into behaviours promoting risk-taking, experimentation and adaptation. More financially strong firms are more well-endowed to absorb the risks of investment in technology, firms with more capable human resources have knowledge on how to manage technological changes, though

Table 4: Construct reliability and validity table

Variables	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
BD	0.886	0.891	0.916	0.687
CT	0.856	0.863	0.902	0.697
HT	0.845	0.850	0.896	0.683
LD	0.883	0.888	0.915	0.683
LT	0.885	0.887	0.916	0.686
NL	0.865	0.865	0.902	0.649
PT	0.848	0.873	0.896	0.684
RR	0.860	0.861	0.899	0.641
TC	0.841	0.843	0.894	0.678
UD	0.882	0.883	0.914	0.679

(Source: Compiled by the author)

Figure 1: Conceptual model of this study

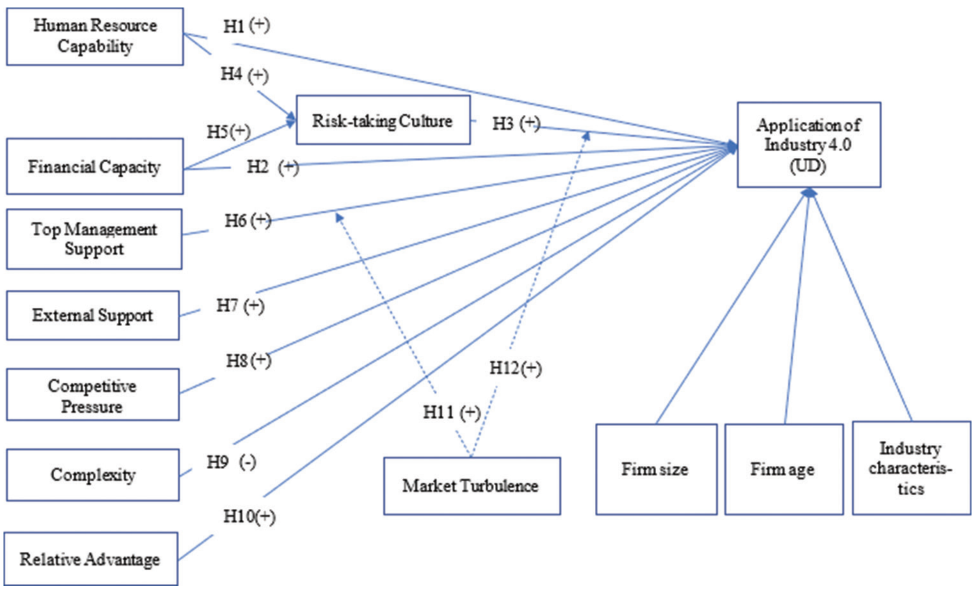
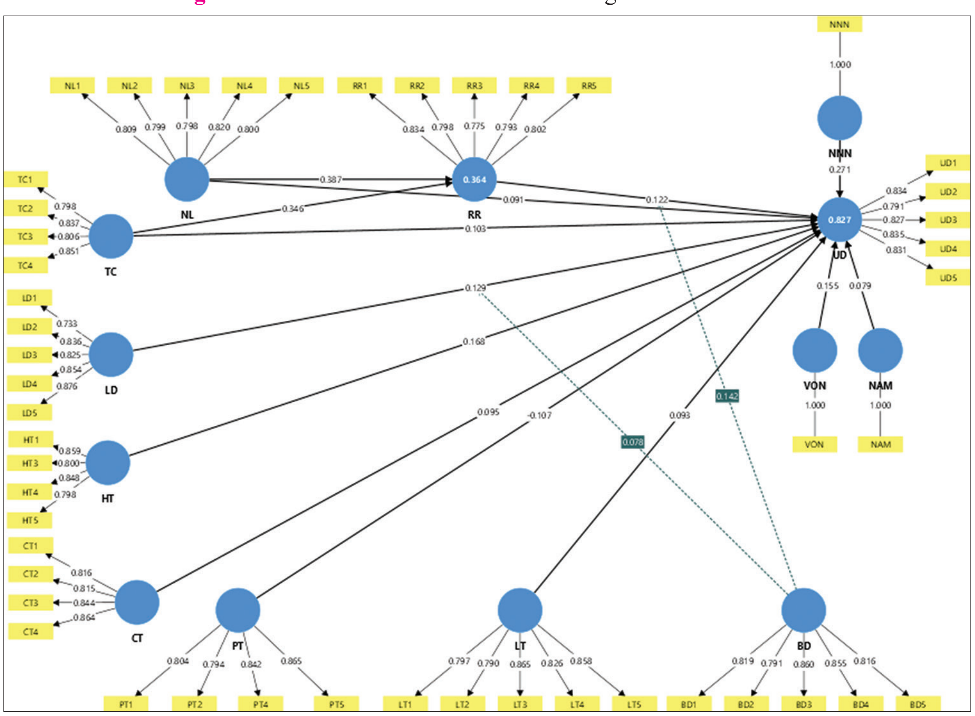


Figure 2: Measurement model after removing observed variables



Source: Data processed by the author using smart partial least squares

Table 5: Heterotrait-monotrait ratio (HTMT) – matrix table

Variables	UD	NL	TC	RR	LD	HT	CT	PT	LT	BD
UD										
NL	0.671									
TC	0.637	0.425								
RR	0.609	0.593	0.571							
LD	0.504	0.159	0.233	0.147						
HT	0.678	0.414	0.273	0.255	0.210					
CT	0.707	0.668	0.362	0.417	0.203	0.560				
PT	0.394	0.058	0.146	0.095	0.152	0.278	0.190			
LT	0.687	0.388	0.370	0.291	0.351	0.567	0.449	0.291		
BD	0.501	0.352	0.334	0.364	0.356	0.309	0.302	0.197	0.287	

(Source: Compiled by the author)

Table 6: Hypothesis testing and impact coefficient table

Hypothesis	Relationship	β	t	P	Result
H_1	Human resource capacity → Application of Industry 4.0 technology.	0.090	2.492	0.013	Accept
H_2	Financial capacity → Application of Industry 4.0 technology.	0.097	3.641	0.000	Accept
H_3	Risk-taking culture → Application of Industry 4.0 technology.	0.124	4.476	0.000	Accept
H_4	Human resource capabilities → Risk culture → Application of Industry 4.0 technology.	0.047	4.015	0.000	Accept
H_5	Financial capacity → Risk culture → Application of Industry 4.0 technology.	0.045	3.901	0.000	Accept
H_6	Top management support → Applying Industry 4.0 technology.	0.132	5.284	0.000	Accept
H_7	External support → Application of Industry 4.0 technology.	0.168	6.211	0.000	Accept
H_8	Competitive pressure → Application of Industry 4.0 technology.	0.088	2.725	0.006	Accept
H_9	Level of complexity → Application of Industry 4.0 technology.	-0.104	4.442	0.000	Accept
H_{10}	Relative advantage → Application of Industry 4.0 technology.	0.099	3.790	0.000	Accept
H_{11}	Market turbulence×Leadership support → Application of Industry 4.0 technology.	0.079	3.307	0.001	Accept
H_{12}	Market turbulence×Risk culture → Application of Industry 4.0 technology.	0.143	5.409	0.000	Accept
CTV1	Firm size→ Application of Industry 4.0 technology	0.155	6.077	0,000	Control variable
CTV2	Firm age→ Application of Industry 4.0 technology	0.079	3.642	0,000	Control variable
CTV2	Industry characteristics→ Application of Industry 4.0 technology	0.271	3.720	0,000	Control variable

(Source: Compiled by the author)

Table 7: R-square and PLSpredict LV summary table

Variables	R-square	R-square adjusted	Q²predict	RMSE	MAE
UD	0.833	0.827	0.720	0.531	0.434
RR	0.367	0.364	0.359	0.804	0.635

(Source: Compiled by the author)

these "capabilities" only achieve true impact in the presence of a risk-taking culture. Our findings serve as confirmation of the view propounding that strategy, in this case, how advantageous resources are transformed into competitive value, is created through social practices.

Risk-taking culture emerged as a significant predictor of adoption itself, highlighting the behavioural and cultural aspects of digital transformation. Because implementation of Industry 4.0 brings uncertainty, process redesign, and technological experimentations, firms that can truly incubate innovation to tolerate failures, and promote learning, tend to achieve successful adoption results. This mediating role of risk-taking culture also suggests that the organizational culture essentially acts as a key intermediary, connecting firm resources with technology adoption.

Technological attributes identified by DOI theory also play a key role in adoption intentions. While relative advantage leads to positive adoption of Industry 4.0, complexity has a negative impact. When considering new technologies, it seems that SMEs assess whether the "pros" outweigh the "cons." Technologies that promise enhancements in efficiency, flexibility, and quality and tend to increase competitiveness are judged to give an expected outcome greater on the side of the positives than the negatives, whereas technical complexity, integration difficulty and cost of implementation lead to less intention, confirming the strong role of technology perception in influencing innovation behaviour.

Furthermore, top management support and competitive pressure had a positive influence on the uptake of Industry 4.0. The commitment of leadership provides strategic direction, allocates resources, and exerts legitimacy on the organisations' attempts at digital transformation; the competitive pressure reminds them of the need for technological advancement.

A particularly important contribution of this study is the identification of market turbulence as a significant boundary condition. The results show that the positive effects of top management support and risk-taking culture are stronger in contexts of high environmental uncertainty. In rapidly changing markets where customer preferences are continuously evolving, technology is advancing quickly, and the competitive landscape is in flux, firms require deeper commitments from management and a greater willingness to experiment. This finding supports contingency theory by implying that the value of these capabilities actually becomes more salient when environmental uncertainty magnifies ‖ as adversity reinforces beneficiaries' ability to adapt and emergency response capabilities.

5.1. Theoretical Implications

This research contributes to the Industry 4.0 adoption literature in three ways. First, it builds on previous research by integrating the Technology-Organization-Environment ("TOE"), Resource-Based View ("RBV"), and Diffusion of Innovation ("DOI") views into one consolidated model. Drawing from the technological, organisational and environmental, and cultural factors concurrently gives us a fuller account of Industry 4.0 adoption in SMEs than studies drawing on only one lens.

Second, the study builds on RBV by highlighting risk-taking culture as an important organizational mechanism used to convert firm resources into technology adoption. Results imply that the strategic value of financial and human resources is not solely conferred by their existence but also by the existence of an organisational culture allowing for risk-taking, experimentation, learning and innovation.

Third, the study further contributes to the Industry 4.0 literature by introducing market turbulence as a relevant contingency factor for determining Industry 4.0 adoption. By showing that environmental uncertainty strengthens top management support and a risk-taking culture, the authors show that the way firms adopt technologies is highly contextual.

5.2. Practical Implications

The results further present significant implications for policy makers (e.g. government institutions), trade associations, and SME managers. For the first group, the strong influence of external support groups suggests that national digitization support policies can be further enhanced to focus not only on direct financial grants, but also to build comprehensive innovation ecosystems (e.g. through technology-transfer programs, development of digital infrastructures, advisory services, or training of employees) that reduce SME's entry thresholds into Industry 4.0.

For industry associations and business-support organizations, the findings suggest the importance of fostering avenues for sharing knowledge and co-creating networks and technology partnerships that aid SMEs in acquiring expertise, developing capabilities, and addressing implementation hurdles concerning advanced digital technologies.

Implications for SME managers: The results suggest that successful Industry 4.0 adoption involves a more holistic mindset as well that entails both technological investment and enhancing organizational capability. Firms should invest in their financial readiness, employee competency enhancement and develop a risk-taking culture that supports experimentation, innovation, and continuous learning. Also, in fast-moving markets, strong leadership commitment to ensure novel digital transformation endeavours respond adequately to environmental uncertainty becomes vital.

Overall, the study findings support viewing Industry 4.0 adoption as a strategic capability of an organization rather just a technology decision. Further, strong explanatory power (adjusted R-squared = 0.827) suggests that integrating TOE, RBV and DOI perspectives; provides significant explanation for digital transformation for SMEs in developing economy-settings.

6. CONCLUSION, LIMITATIONS AND FUTURE RESEARCH

The adoption of Industry 4.0 by small and medium enterprises (SMEs) is a complex phenomenon defined by a blend of organizational resources, technology, environment, and culture. Focusing on these four dimensions through the lens of the TOE framework, resource based view (RBV) and diffusion of innovation (DOI), this study establishes a comprehensive model with mediating and moderating effects, yielding three primary conclusions. First, external support has the greatest effect on SMEs' adoption of Industry 4.0 in Southeast Vietnam. Second, organizations leveraging their resources to create a risk-taking culture encouraging experimentation and innovation will achieve better results with Industry 4.0 adoption. Third, the impact of leadership commitment and risk-taking culture will be more pronounced when SMEs experience higher levels of market uncertainty. The predictive and explanatory power of the model underscored the soundness of the framework (Adjusted $R^2 = 0.827$; Q^2 Predict = 0.720).

The current findings suggest that, from an operational perspective, the adoption of Industry 4.0 should occur as part of an overall organisational change management project rather than simply a technical project. Therefore, policymakers should develop comprehensive innovation ecosystems and provide extensive support beyond what traditional technology support initiatives have offered. Such support can help build the capacity required to implement Industry 4.0 projects, eliminate barriers to project completion, strengthen the necessary infrastructure, and provide advisory services, training opportunities, and connections with organisations that can support project implementation. These forms of assistance may be integrated into a comprehensive support service framework.

Industry associations and other organisations can also accelerate the adoption of Industry 4.0 by providing firms with industry knowledge-sharing networks and collaborative technology-related partnerships. To successfully execute their digital transformation strategy, SMEs must also concurrently achieve all of these: Financial readiness, human resources; Leadership buy-in; Corporate culture; External connections. Investments in technology may not continue to yield value unless the elements within an organisation exist to enable that investment; in other words, if an organization does not have the capacity to support then the organisations supporting the technology investment will not provide the expected return(s) on investment for an organisation.

Overall, this study concludes that Industry 4.0 adoption is shaped by the combined influence of technological, organizational, environmental, and cultural factors.

This study identifies several limitations that could frame directions for future research. The primary limitation for this study is its cross-sectional design; this limits the ability to infer causality and fail to provide an understanding of the dynamic nature of Industry 4.0 adoption. Since digital transformation is an evolving process, future longitudinal research could explore how organizational resources, a culture of risk-taking, and the environment influence Industry 4.0 adoption at various stages of technology maturity.

Second, data was collected with a key informant from inside the organisation. Although using the senior management/business owners would be acceptable as a source for strategic/technical decision-making, there is potential to create a perception of bias by relying on only one source. Future research could use a multi-informant approach that includes collecting data from various levels and functions across the organisation in order to create a more accurate assessment of overall organisation performance.

Third, findings were determined from interviews conducted with small and medium-sized enterprises located in Southeast Vietnam. These interviews may have occurred in a specific cultural or economic environment that is different and could affect how those results translate into other cultures or economies. Future studies need to use a comparative study design to compare this framework across regions and nations in order to determine whether this framework remains valid across multiple operational environments.

Fourth, the results of our study indicate that there is an acceptable level of reliability and validity of the measurement model; however, a number of the indicators were removed from the measurement model during the purification. Future research will be directed toward extending the utility of the measurement instruments to other sectors and other developing countries as well as continuing their validation.

Finally, the current research lays the groundwork for identifying conditions that would trigger the decision-making process of organizations to adopt I4.0; however, what has not been considered in the current research is the effect of I4.0 on an organization, after the decision to adopt has been made. Future research should build on this study's framework and investigate the extent to which the adoption of I4.0 leads to the following areas: innovation performance, operational efficiency, supply chain resilience, sustainability performance, and competitive advantage (building from Dynamic Capability Theory and Institutional Theory will provide insights into how firms have the outward flexibility to continually reconfigure resources and adapt to environmental forces during their digital transformation). Overall, a more thorough understanding of the ways in which I4.0 technologies create long-term value for SMEs would be achieved with respect to both of these aspects.

REFERENCES

Amin, A., Bhuiyan, M.R.I., Hossain, R., Molla, C., Poli, T.A., Milon, M.N.U. (2024), The adoption of industry 4.0 technologies by using the technology organizational environment framework: The mediating role to manufacturing performance in a developing country. Business Strategy and Development, 7(2), e363.

Anshari, M., Almunawar, M.N. (2022), Adopting open innovation for SMEs and industrial revolution 4.0. Journal of Science and Technology Policy Management, 13(2), 405-427.

Barney, J. (1991), Firm resources and sustained competitive advantage. Journal of Management, 17(1), 99-120.

Cirera, X., Comin, D., Cruz, M., Lee, K.M., Soares Martins-Neto, A. (2021), Firm-Level Technology Adoption in Vietnam. Washington, DC: World Bank.

Fernando, Y., Wahyuni T.D.I.S., Gui, A., Ikhsan, R.B., Mergeresa, F., Ganesan, Y. (2023), A mixed-method study on the barriers of industry 4.0 adoption in the Indonesian SMEs manufacturing supply chains. Journal of Science and Technology Policy Management, 14(4), 678-695.

Fornell, C., Larcker, D.F. (1981), Evaluating structural equation models with unobservable variables and measurement error. Journal of Marketing Research, 18(1), 39-50.

Ghobakhloo, M., Iranmanesh, M., Vilkas, M., Grybauskas, A., Amran, A. (2022), Drivers and barriers of industry 4.0 technology adoption among manufacturing SMEs: A systematic review and transformation roadmap. Journal of Manufacturing Technology Management, 33(6), 1029-1058.

Grooss, O.F., Presser, M., Tambo, T. (2022), Surround yourself with your betters: Recommendations for adopting Industry 4.0 technologies in SMEs. Digital Business, 2(1), 100046.

Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E. (2009), Multivariate Data Analysis. 7th ed. New Jersey: Pearson Prentice Hall.

Hair, J.F., Risher, J.J., Sarstedt, M., Ringle, C.M. (2019), When to use and how to report the results of PLS-SEM. European Business Review, 31(1), 2-24.

Henseler, J., Ringle, C.M., Sarstedt, M. (2015), A new criterion for assessing discriminant validity in variance-based structural equation modeling. Journal of the Academy of Marketing Science, 43(1), 115-135.

Hock, M., Ringle, C.M. (2010), Local strategic networks in the software industry: An empirical analysis of the value continuum. International Journal of Knowledge Management Studies, 2(2), 132-151.

Hock-Doepgen, M., Clauss, T., Kraus, S., Cheng, C.F. (2021), Knowledge management capabilities and organizational risk-taking for business model innovation in SMEs. Journal of Business Research, 130, 683-697.

Indiani, N.L.P., Keshminder, J.S., Wiratama, N.I., Amertha, G.S. (2025), Unlocking e-commerce potential in SMEs: An integrative framework for adoption in emerging markets. Humanities and Social Sciences Communications, 12, 766.

Intalar, N., Ueki, Y., Jeenanunta, C. (2024), Enhancing competitiveness: Driving and facilitating factors for industry 4.0 adoption in Thai manufacturing. Economies, 12(8), 210.

Jaworski, B.J., Kohli, A.K. (1993), Market orientation: Antecedents and consequences. Journal of Marketing, 57(3), 53-70.

Jayashree, S., Reza, M.N.H., Malarvizhi, C.A.N., Gunasekaran, A., Rauf, M.A. (2022), Testing an adoption model for industry 4.0 and sustainability: A Malaysian scenario. Sustainable Production and Consumption, 31, 313-330.

Kock, N. (2015), Common method bias in PLS-SEM: A full collinearity assessment approach. International Journal of e-Collaboration, 11(4), 1-10.

Lawrence, P.R., Lorsch, J.W. (1969), Organization and Environment: Managing Differentiation and Integration. Irwin. Available from: https://cir.nii.ac.jp/crid/1970867909784112773

Le, V.L.T., Nguyen, T.H., Pham, K.D. (2023), What drives Industry 4.0 technologies adoption? Evidence from a SEM-

Neural network approach in the context of Vietnamese firms. Sustainability, 15(7), 5969.

Masood, T., Sonntag, P. (2020), Industry 4.0: Adoption challenges and benefits for SMEs. Computers in Industry, 121, 103261.

Mittal, S., Khan, M.A., Romero, D., Wuest, T. (2018), A critical review of smart manufacturing and Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of Manufacturing Systems, 49, 194-214.

Mustafa, S., Rana, S., Naveed, M.M. (2024), Identifying factors influencing industry 4.0 adoption for sustainability. Journal of Manufacturing Technology Management, 35(2), 336-359.

Madhusanka, B.G.D.A., Ramadass, S., Rajagopal, P., Herath, H.M.K. K.M.B. (2024), Artificial intelligence-based system for gaze-based communication. CRC Press. doi: 10.1201/9781003373940

Nunnally, J.C., Bernstein, I.H. (1994), Psychometric Theory. 3rd ed. New York McGraw-Hill. Available from: https://www.scirp.org/reference/ReferencesPapers?ReferenceID=1017362

Rogers, E.M. (2003), Diffusion of Innovations. 5th ed. Mumbai: Free Press.

Shahzad, A., Bin Zakaria, M.S.A., Kotzab, H., Makki, M.A.M., Hussain, A., Fischer, J. (2023), Adoption of fourth industrial revolution 4.0 among Malaysian small and medium enterprises (SMEs), Humanities and Social Sciences Communications, 10(1), 1-14.

Tamvada, J.P., Narula, S., Audretsch, D., Puppala, H., Kumar, A. (2022), Adopting new technology is a distant dream? The risks of implementing Industry 4.0 in emerging economy SMEs. Technological Forecasting and Social Change, 185, 122088.

Techanamurthy, U., Iqbal, M.S., Abdul Rahim, Z. (2025), Industry 4.0 readiness and strategic plan failures in SMEs: A comprehensive analysis. PLoS One, 20(5), e0324052.

Tornatzky, L.G., Fleischer, M., Chakrabarti, A.K. (1990), The Processes of Technological Innovation. Available from: https://cir.nii.ac.jp/crid/1130000796720150784

Tornatzky, L.G., Fleischer, M., Chakrabarti, A.K. (1990), The Processes of Technological Innovation. Maryland: Lexington Books.

Wong, A.P.H., Kee, D.M.H. (2022), Driving factors of industry 4.0 readiness among manufacturing SMEs in Malaysia. Information, 13(12), 552.

Zamani, S.Z. (2022), Small and Medium Enterprises (SMEs) facing an evolving technological era: A systematic literature review on the adoption of technologies in SMEs. European Journal of Innovation Management, 25(6), 735-757.