

RESEARCH PAPER

Industry 4.0 adoption for supply chain performance in Tunisian companies: the mediating and moderating effect of resilience and visibility

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ABSTRACT

Goal: This study aims to investigate the direct and indirect effects of Industry 4.0 (I4.0) on supply chain performance (SCP) in Tunisian firms, by testing the mediating role of supply chain resilience (SCRes) and the moderating role of supply chain visibility (SCV).

Design/Methodology/Approach: The analysis collected data from 81 Tunisian companies across diverse sectors, including manufacturing, agri-food, pharmaceutical, and other activities using Partial Least Squares Structural Equation Modeling (PLS-SEM) to test the theoretical hypotheses. Smart PLS 4.0 is the statistical software used in this survey.

Results: Supply chain resilience significantly mediates this relationship, indicating that I4.0's full performance benefits are contingent upon strengthening resilience capabilities. Additionally, supply chain visibility positively moderates the link between I4.0 and resilience, demonstrating that higher visibility amplifies the positive effect of I4.0 on SCRes. These findings emphasize that I4.0 generates maximum impact only when combined with resilience and visibility efforts.

Limitations of the investigation: This study has five main limitations (cross-sectional design, moderate sample size, self-reported measures, focus on only three I4.0 technologies, and single-country context), which future research should address through longitudinal designs, larger samples, objective data, and cross-country comparisons.

Practical implications: This research offers an actionable plan for Tunisia's industrial evolution, showing how a strategic focus on I4.0-driven resilience and visibility can directly boost the private sector's competitiveness, strengthen the national economy, and ensure a more prosperous position in the global market.

Originality/Value: This study extends Qader et al. (2022) by providing the first empirical examination of their integrated I4.0, resilience, visibility, and performance framework in an African emerging economy (Tunisia). While the conceptual model and hypotheses are adapted from Qader et al. (2022), we contribute by validating the framework in a context characterized by fragmented logistics, small and medium-sized enterprise (SME) dominance, and high information asymmetry, conditions that may amplify the importance of visibility mechanisms. The findings offer context-specific insights for other emerging economies.

Keywords: Operational and financial performances; Industry 4.0; Supply chain visibility; Supply chain resilience; Mediating and moderating roles.

1 INTRODUCTION

The COVID-19 pandemic significantly affected organizations across multiple aspects, from inventory management to production planning. These changes suggest a lasting evolution in how

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companies approach their logistics management in an increasingly volatile world. Several researchers have examined the repercussions of this health crisis, highlighting how it has exposed the vulnerabilities and limitations of global supply chains (Chopra *et al.*, 2019; Sarkis, 2021; Ivanov, 2020). Their findings indicate that inadequate supply chain resilience played a central role in poor supply chain performance during the COVID-19 pandemic. Supply chain resilience (SCRes) indicates a proactive ability of the supply chain (SC) to avoid most disruptions in the supply chain and to mitigate the consequences of those that do occur for effective supply chain (SC) performance (Mubarik *et al.*, 2021). A supply chain is, therefore, considered resilient if it is not, or only slightly, impacted by an event which could, in normal times, have compromised its smooth running, or even paralyzed it.

Similarly, firms need to develop an adequate level of supply chain visibility (SCV) to enhance SC resilience and SC performance (Xie *et al.*, 2020). It aims to enhance the supply chain by making all data available to stakeholders from the supplier to the end customer. Having an overview of every link in the supply chain can have a significant impact on every operational aspect of your business.

By integrating I4.0, companies can benefit from predictive maintenance, which analyzes performance and detect in advance drops in profitability and/or obsolescence of machines and devices. The advantages of I4.0 for companies are diverse and combined, they will allow the firm to increase its value creation potential while being more competitive, more modern, closer to the customer and, last but not least, more respectful of the environment. I4.0 also helps improve supply chain performance by enhancing the SCRes and SCV (Khan and Emon, (2025), Vasconcelos *et al.*, (2025), Silva *et al.*, (2024), Al-Talib *et al.*, (2020); Dubey *et al.*, (2020); Zhu and Kouhizadeh, (2019); Tao *et al.*, (2019); Whitmore *et al.*, (2015)).

Although extensive research has highlighted I4.0's role in enhancing firm performance, its specific impact on supply chain resilience and performance remains a significant source of uncertainty for many companies. This uncertainty motivates our research, which seeks to address the following objectives: first, to examine the role of I4.0 in improving supply chain resilience and subsequent supply chain performance (SCP); and second, to evaluate the mediating contributions of supply chain resilience and visibility to the I4.0 SCP relationship.

To achieve these objectives, we undertook comprehensive data collection from a diverse range of 81 Tunisian companies including manufacturing industry, agri-food, pharmaceutical and other activities, using PLS-SEM to test the theoretical hypotheses. We begin with an overview of the demographics of our sample, before diving into an in-depth analysis of specific I4.0 indicators, resilience and visibility. We try to explore the data that inform our understanding of the future of the Tunisian supply chain in the era of I4.0.

Our work offers several key contributions. First, we build directly on Qader *et al.* (2022), who developed and tested the integrated mediation and moderation framework linking I4.0, supply chain resilience, supply chain visibility, and supply chain performance. We do not claim to introduce this framework. Rather, we extend their work by providing the first empirical validation of the model in an African emerging economy (Tunisia), thereby testing its generalizability beyond the developed and emerging manufacturing contexts in which it was originally developed. Second, we generate context-specific insights showing that the visibility moderation effect holds, and may be even more pronounced, in a setting characterized by fragmented logistics, SME dominance (over 90% with fewer than 100 employees), and high information asymmetry. These conditions make visibility a critically amplificative factor for the effect of I4.0 on resilience, a finding that may generalize to other emerging economies. Third, we offer actionable managerial and policy implications for the industrial upgrading strategy of Tunisia, showing how the visibility amplification effect translates into concrete priorities for SME-dominated supply chains.

In addition, this work integrates the resource-based view and information processing theory to elucidate the complex mechanisms (mediation and moderation) through which I4.0 creates value. The findings also offer a clear strategic roadmap for managers, showing that investments in I4.0 must be coupled with efforts to enhance visibility and resilience to fully realize performance benefits.

2 LITERATURE

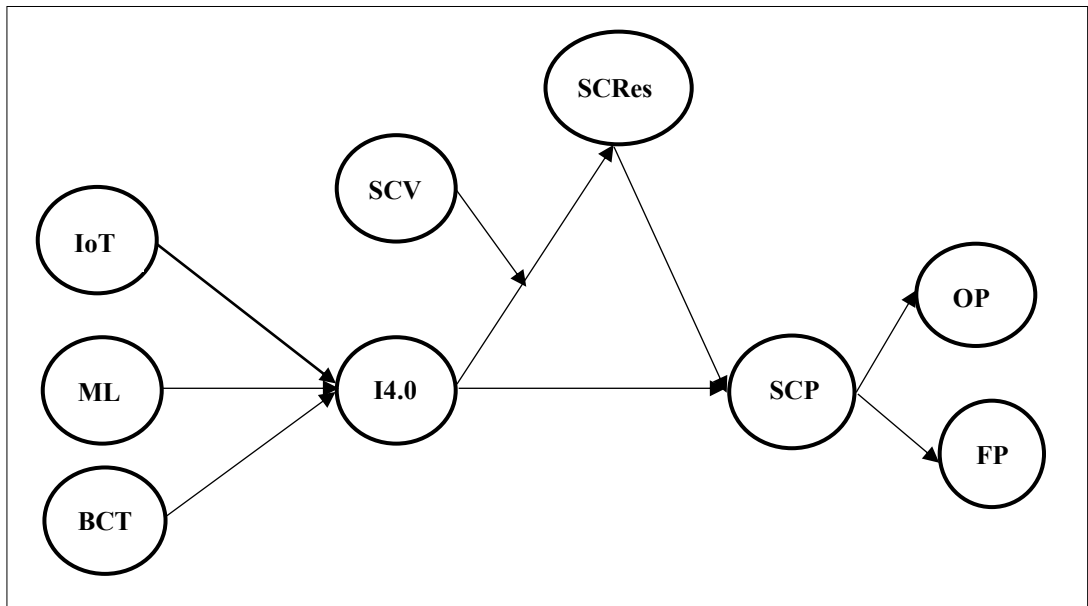
2.1 Theoretical foundations

This study builds on Information Processing Theory (IPT) (Galbraith, 1974) and the Resource-Based View (RBV). IPT considers organizations as systems that must process information to minimize uncertainty and achieve optimal performance. Central to this perspective is the concept of fit (Tushman and Nadler, 1978), which posits that alignment between an organization's information processing needs and its capabilities is essential. These needs arise from

environmental uncertainty, which requires quality information for effective decision-making (Thompson, 1967). The RBV complements this by explaining the internal resources that constitute these capabilities.

The RBV shows that a firm's competitive advantage stems from its effective management of valuable resources, which can be physical (e.g., equipment) or non-physical (e.g., human capital, knowledge, and skills) (Wernerfelt, 1984; Barney, 1991). While physical resources address operational needs, their optimal deployment can foster collaboration and transformation, thereby creating a sustainable competitive edge (Chatterjee and Wernerfelt, 1991; Hill *et al.*, 1992). To better understand the impact of external pressures, RBV is integrated with Institutional Theory. This synthesis offers a powerful lens to examine environmental uncertainties and supply chain complexities, facilitating the development of strategies aimed at bolstering resilience and performance. The Figure 1 presents the conceptual framework derived from this theoretical integration.

Figure 1 - Conceptuel Model



Source: Qader *et al.* (2022).

2.2 Theoretical integration and hypothesis mapping

To address the insufficient integration of Information Processing Theory (IPT), the Resource-Based View (RBV), and Institutional Theory, we now explicitly delineate how each framework justifies a distinct part of our model. IPT justifies Supply Chain Visibility (SCV) as a moderator : SCV reduces information uncertainty and information asymmetry between supply chain partners, thereby strengthening the positive effect of Industry 4.0 adoption on supply chain resilience (Galbraith, 1974; Tushman and Nadler, 1978). RBV justifies Industry 4.0 technologies (IoT, ML, BCT) as strategic resources that satisfy the VRIO criteria (valuable, rare, inimitable, organizationally supported). Consequently, I4.0 is modelled as an independent variable directly affecting supply chain performance and resilience (Barney, 1991). Institutional Theory explains external pressures (coercive, mimetic, normative) as antecedents that drive firms to adopt I4.0 and SCV practices for legitimacy reasons beyond efficiency (DiMaggio & Powell, 1983). Table 1 links each theory to its corresponding hypothesis, core construct, and causal mechanism. This table clarifies that IPT supports the moderation hypotheses (H4), RBV supports the direct-effect hypotheses (H1, H2a, H2b), and Institutional Theory provides the rationale for external pressures (H3a, H3b).

For H1 (I4.0→SCP), prior studies conflate I4.0 with general information technologies. The gap is the lack of isolated I4.0 effects on performance. For H2 (mediation via SCRes), existing research treats resilience as an antecedent, not a mechanism and the gap is whether I4.0's performance impact is fully transmitted through resilience. For H4 (moderation by SCV), previous work models visibility as a direct driver, not as a boundary condition and the gap is the lack of a test for amplification effects. These gap statements precede each hypothesis justification.

Table 1 - Theoretical integration and hypothesis mapping

Theory	Core Construct	Role in Model	Related Hypothesis	Causal Mechanism
Information Processing Theory (IPT)	Supply Chain Visibility (SCV)	Moderator	H4: SCV moderates the I4.0 → SCRes relationship.	Reduces information uncertainty and asymmetry between partners
Resource-Based View (RBV)	Industry 4.0 technologies (IoT, ML, BCT)	Independent variable	H1, H2a, H2b: I4.0 → SCP; I4.0 → SCRes; SCRes → SCP	I4.0 as VRIN resource generating sustained competitive advantage
Institutional Theory	External pressures (coercive, mimetic, normative)	Antecedent (contextual driver)	H3a, H3b: External pressures → I4.0 adoption and SCV adoption	Legitimacy-seeking behavior beyond efficiency motives

Source: The authors themselves.

2.3 The theoretical hypothesis

Table 2 detail the main theoretical hypotheses analyzed in the present work.

Table 2 - The theoretical hypotheses

Hypothesis 1	I4.0 has a positive impact on supply chain performance.
Hypothesis 2	Supply chain resilience mediates the effect of I4.0 on supply chain performance.
Hypothesis 2.a	I4.0 has a positive impact on supply chain resilience.
Hypothesis 2.b	The positive impact of supply chain resilience on supply chain performance.
Hypothesis 3	Supply chain visibility improves companies supply chain resilience.
Hypothesis 4	Supply chain visibility moderates the relationship between I4.0 and supply chain resilience.

Source: Qader *et al.* (2022).

2.4 Measured variables and items

By integrating I4.0, companies can benefit from predictive maintenance, which analyze performance and detect in advance drops in profitability and/or obsolescence of machines and devices. The pillars of I4.0 covered developed technologies which are internet of things, the internet of services, augmented reality, industrial robotics, cyber-physical systems, cloud computing, blockchain, big data analytics, digital twins, machine learning, artificial intelligence, and additive manufacturing across the product life-cycle. The main technologies used in our context in literature are internet of things, blockchain and machine learning.

The machine learning (ML) elements were carefully developed in-house, drawing on the innovative conceptual framework established in the study by Nagar *et al.* (2021). To ensure the robustness of the measurement scale for these elements, we implemented a pilot test, seeking the expertise of qualified evaluators. This preliminary process made it possible to consolidate the reliability of the methodology adopted.

A rigorous selection process guided our choice of measurement *elements* drawing on the reservoir of knowledge from previous studies *items, anchored in prior studies*. Specifically, the characteristic elements of blockchain (BC) technology draw heavily on the influential work of Van Hoek *et al.* (2001). Similarly, the elements related to the internet of things (IoT) draws on the work of Al-Talib *et al.* (2020). As for the elements of SCRes, we carefully selected in accordance with the insightful contributions of Juan *et al.* (2022).

Furthermore, the elements of operational performance (OP) and financial performance (FP) within the supply chain base on the methodological work of Abeysekara *et al.* (2019). Finally, the measurement elements relating to supply chain visibility (SCV) build on the significant findings of Williams *et al.* (2013).

It is essential to emphasize that all of the measurement items, found in table 3, use a standardized five-point Likert scale. This scale, where 1 represents “strongly disagree” and 5 represents “strongly agree,” provides a consistent basis for evaluating participants’ responses.

Table 3 - Items related to each variable studied in this paper

Internet of things (IoT)	
IoT1	The implementation of IoT based technology enhances productivity and reliability while simultaneously minimizing costs.
IoT2	The efficient flow of information provided by Internet of Things technology enhances trust between partners.
IoT3	The Internet of Things helps continuously update experience and knowledge, such as in customer service.
IoT4	The inherent flexibility of IoT-based systems enables them to effectively address unanticipated problems.
IoT5	Internet of Things technology demonstrates the agility to rapidly achieve necessary results within suitable timeframes.
Machine learning (ML)	
ML1	ML provides the foundation for designing intelligent workspaces.
ML2	ML helps support the decision-making process
ML3	ML accelerates operations
ML4	ML strengthens cross-functionality between teams
ML5	ML facilitates the innovation of new products and services.
Blockchain technology (BCT)	
BCT 1	Blockchain technology is helpful in reducing production lead time
BCT 2	Blockchain is helpful in improving the frequency of new product introductions
BCT 3	Blockchain can help in reducing delivery times
BCT 4	Blockchain is useful for promoting product personalization
BCT 5	Blockchain can help company in detecting and adapting to change in market needs
Supply chain resilience (SCRes)	
SCRes1	Our company possesses the capability to anticipate and mitigate disruption risks at their source.
SCRes2	Through advanced monitoring of supply chain processes, we prevent disruptions before they occur.
SCRes3	Our company has a rapid-response capability for managing supply chain disruptions.
SCRes4	We quickly assess and mobilize supply chain resources in the immediate aftermath of a disruption.
SCRes5	We are capable of restoring our supply chain to full operation after a disruption.
SCRes6	We possess the capability to dynamically reallocate supply chain resources to guarantee a full return to normal operations post-disruption
Supply chain visibility (SCV)	
SCV1	We maintain open communication with our key suppliers, who consistently provide timely stock-level information
SCV2	Our suppliers furnish us with timely advance shipping notifications (ASNs).
SCV3	Our process involves synthesizing information from diverse sources to build a comprehensive view of market supply.
SCV4	We have real-time visibility into the status of finished goods across our entire distribution network, including distribution centers and in-transit shipments.
Operational performance (OP)	
OP1	Our brands benefit from high levels of customer recognition
OP2	We maintain a strong and established reputation for quality.
OP3	Our company cultivates enduring, strategic relationships with its customers.
OP4	Our commitment is to provide customers with the perfect quantity and quality at the perfect time.
Financial performance (FP)	
FP1	We are experiencing high growth in market share
FP2	The company has demonstrated a high rate of sales expansion

FP3	We maintain a strong market presence with our product portfolio.
FP4	We achieve high profitability on our sales.

Source: (Al-Talib *et al.*, 2020 ; Nagar *et al.*, 2021 ; Van Hoek *et al.*, 2001 ; Juan *et al.*, 2022 ; Williams *et al.*, 2013 ; Abeysekara *et al.*, 2019).

3 METHODOLOGY

3.1 Data collection instrument

This study undertook comprehensive data collection from a diverse range of Tunisian companies, spanning key sectors such as manufacturing, agribusiness, pharmaceutical companies, and other relevant industries. The selection of these sectors was based on their advanced adoption of I4.0 technologies, including IoT, ML, and BCT. To ensure optimal participation from respondents, we sent frequent reminders by email and via the LinkedIn platform. Data collection combined electronic questionnaires distributed via email and in-person interviews conducted during company visits.

Initially, a total of 90 responses is collected from professionals working in various sectors in Tunisia. Following the application of rigorous data verification measures, the final sample consists of 81 responses, which meaningfully and reliably represent the perspective of the Tunisian companies involved in this study.

Companies were selected through convenience sampling from Tunisian industry directories provided by the Tunisian Union of Industry, Trade and Handicrafts (UTICA) and the National Agency for Industrial Promotion (APII), targeting firms with known adoption of at least one Industry 4.0 technology. Of 210 contacted firms, 90 completed and returned usable questionnaires, yielding a response rate of 42.9 percent. To assess non-response bias, we compared early and late respondents across key firm characteristics (number of employees, annual revenue, and industry sector) using independent samples t tests. No statistically significant differences were found, as all p values exceeded the 0.10 threshold, indicating that non-response bias is unlikely to threaten the validity of our findings (Armstrong & Overton, 1977). Regarding common method bias, we conducted Harman's single-factor test on all self-reported items. A single-factor test extracted less than 50% of the total variance, confirming that common method bias is unlikely (Podsakoff *et al.*, 2003).

To ensure the relevance and clarity of the measurement items for the Tunisian context, we followed a rigorous back-translation procedure. The original English items were first translated into French, then into Arabic, and finally back into English by a different set of translators. This process helped us detect and correct any ambiguities or cultural mismatches. Next, we conducted a pilot test with 15 academic experts and 10 industry managers. Based on their feedback, we revised items that lacked face validity or were difficult to understand in a Tunisian business setting. The final set of items, reported in Table 3, all achieved factor loadings above 0.70 (see Table 6), confirming their strong measurement properties.

We determine The sample size of 81 based on established guidelines for Partial Least Squares Structural Equation Modeling (PLS-SEM). Following the '10-times rule' (Hair *et al.*, 2011), the minimum required sample size should be ten times the largest number of structural paths pointing to a single construct. Our model has a maximum of three paths pointing to SCRes (from I4.0, SCV, and the interaction term for moderation). Thus, the minimum required sample size is 30. With 81 responses, our sample exceeds this minimum requirement by a factor of 2.7. Furthermore, a priori power analysis using G*Power (Faul *et al.*, 2009) with $\alpha = 0.05$, a medium effect size ($f^2 = 0.15$), and three predictors indicates that a sample of 77 would achieve a power of 0.80. Our sample of 81 therefore meets the recommended power threshold. While larger samples are always preferable, our sample size is adequate for the complexity of our research model.

Table 4 - Profiling and demographics

Characteristics	Count	Frequency
Activity area:		
Manufacturing industry	31	38.3%
Agri-food	26	32.1%
Pharmaceutical	8	9.9%
Other activities	16	19.7%

Position occupied:		
Senior manager	41	50.6%
Middle manager	23	28.4%
Employee	17	21%
Education level:		
Master's degree or more	34	42%
License	32	39.5%
High school diploma	15	18.5%

Source: The authors themselves.

The reduction from the initial sample was justified by our approach to ensuring data quality. We rigorously applied data verification criteria to maintain the consistency and reliability of the final sample.

Data relating to the sector of activity, position occupied, and level of education of the participants will be detailed in the table 4, thus offering an in-depth view of the demographic diversity of the sample.

3.2 Analytical methods

Our methodological choice is based on the use of the Structural Equation Modeling (SEM) method with the Partial Least Squares (PLS) approach to examine the relationships developed in this study. PLS-SEM was favored due to its ability to model complex relationships (Akter *et al.*, 2017) and to study these relationships accurately while avoiding collinearity issues and indeterminacy of factors (Moshtari, 2016). Smart PLS 4.0 was the statistical software used in this survey.

The main objective of our research is to analyze the impact of I4.0 adoption on Supply chain resilience and on operational and financial performances. The estimation process of our model includes two distinct steps. First, identifying the measurement model helps assess validity and reliability statistics. Then, the structural model analysis is carried out to highlight the underlying relationships between the variables (Dubey *et al.*, 2020).

4 RESULTS

4.1 Descriptive analysis

This section presents a summary statistics of the responses provided to the questionnaire items, highlighting the central tendencies as well as the variations observed. Key metrics such as mean, standard deviation (St dev), minimum, and maximum are used to quantify the dispersion and centrality of responses. Additionally, response frequencies for each item are presented to provide perspective on the overall distribution of opinions. This analytical approach aims to provide a detailed understanding of the nuances inherent in the responses, thereby contributing to a more informed interpretation of the study results. In Table 5, the data analyzes are presented in detail.

Table 5 - Univariate statistical analysis of the variables and items studied

Items	Descriptive statistics				Effective per response				
	Minimum	Maximum	Mean	St dev	1	2	3	4	5
IoT1	1,0	5,0	3,568	0,8206	1	6	28	38	8
IoT2	1,0	5,0	3,556	0,9354	3	4	31	31	12
IoT3	1,0	5,0	3,494	0,9890	2	8	34	22	15
IoT4	1,0	5,0	3,630	0,8433	0	7	28	34	12
IoT5	1,0	5,0	3,630	0,9006	1	7	26	34	13
ML1	1,0	5,0	3,679	1,0704	6	4	15	41	15
ML2	1,0	5,0	3,765	1,0755	5	2	22	30	22
ML3	1,0	5,0	3,815	0,9369	2	4	20	36	19
ML4	1,0	5,0	3,704	0,9804	1	8	24	29	19
ML5	1,0	5,0	3,815	0,8383	0	5	22	37	17
BCT1	1,0	5,0	3,642	1,0643	5	5	20	35	16

BCT2	1,0	5,0	3,827	0,9459	1	5	23	30	22
BCT3	1,0	5,0	3,877	0,9405	1	5	20	32	23
BCT4	1,0	5,0	4,000	0,8803	2	1	16	38	24
BCT5	1,0	5,0	3,864	0,9321	2	4	17	38	20
SCRE1	1,0	5,0	2,531	0,8229	4	41	27	7	2
SCRE2	1,0	5,0	2,556	0,9747	11	29	28	11	2
SCRE3	1,0	5,0	3,049	0,8047	2	16	41	20	2
SCRE4	1,0	5,0	3,198	0,7813	1	14	35	30	1
SCRE5	1,0	5,0	3,654	0,8826	2	6	20	43	10
SCRE6	1,0	5,0	3,840	0,9281	2	4	18	38	19
SCV1	1,0	5,0	3,469	0,8229	2	7	27	41	4
SCV2	1,0	5,0	3,556	0,8660	0	9	29	32	11
SCV3	1,0	5,0	3,506	0,8235	0	9	30	34	8
SCV4	1,0	5,0	3,214	0,7882	3	11	32	29	6
OP1	1,0	5,0	3,704	0,9144	2	6	19	41	13
OP2	1,0	5,0	3,877	0,8998	2	5	11	46	17
OP3	1,0	5,0	3,926	0,8913	2	1	20	36	22
OP4	1,0	5,0	3,852	1,0014	2	6	17	33	23
FP1	1,0	5,0	3,679	0,9978	4	4	21	37	15
FP2	1,0	5,0	3,741	0,9718	3	5	18	39	16
FP3	1,0	5,0	3,765	0,9390	3	4	17	42	15
FP4	1,0	5,0	3,840	0,9281	3	3	15	43	17

Source: The authors themselves.

The statistical analysis of the data collected constitutes a crucial step in our study aimed at assessing participants' perceptions and attitudes towards I4.0 technologies, supply chain resilience, visibility of the supply chain, and operational and financial performance. This section aims to provide a detailed overview of the results obtained from the questionnaire.

Through descriptive statistical measures, we will explore the central tendencies, the dispersion of responses and the average perceptions for each item of the questionnaire. These analyzes will provide significant insights into how participants perceive the different dimensions of our study.

The aim of this analysis is to provide a solid basis for the further discussion and interpretation of the results, thus allowing the identification of areas where specific actions can be considered to improve specific aspects related to our study.

Before moving to hypothesis testing, we aim to clarify three points that readers sometimes find confusing. First, what exactly do we mean by the three Industry 4.0 technologies we studied ? Internet of Things, or IoT, refers to networked sensors and devices that share real time data, for example tracking a shipment's temperature and location. Machine learning (ML) refers to algorithms that learn from past data to help with predictions or decisions, such as forecasting demand or flagging anomalies. Blockchain technology, or BCT, is a shared, tamper proof ledger that records transactions without a central authority, which is useful for tracing products across a supply chain. Each of these is measured by the items listed in Table 2. Second, readers often ask about the difference between mediation and moderation. In plain terms, mediation, which is Hypothesis 2, answers the question of how I4.0 affects supply chain performance. The answer is that it does so indirectly, by first building resilience. Moderation, which is Hypothesis 4, answers a different question : under what conditions does I4.0 work better? The answer is that when visibility is high, the effect of I4.0 on resilience becomes stronger. So mediation is about the mechanism, while moderation is about the context. Third, we want to be clear about how to read our statistical results. Take the path from I4.0 to resilience with a coefficient of 0.615. This means that if two companies are otherwise similar, the one with a one point higher score on I4.0 adoption tends to have a 0.615 point higher score on resilience. We do not claim that I4.0 causes or guarantees resilience, because our design is cross sectional, so we speak of associations, not certainties. The same cautious interpretation applies to all coefficients reported below.

4.2 Measurement model

We commenced the analytical procedure with the estimation of the measurement model within the Structural Equation Modeling (SEM) framework. To establish the validity of the reflective measurement model, we examined constructs for internal consistency (Cronbach's alpha and composite reliability), convergent validity (average variance extracted (AVE)), indicator reliability, and discriminant validity (Fornell-Larcker criterion). Table 6 summarizes the corresponding SmartPLS results.

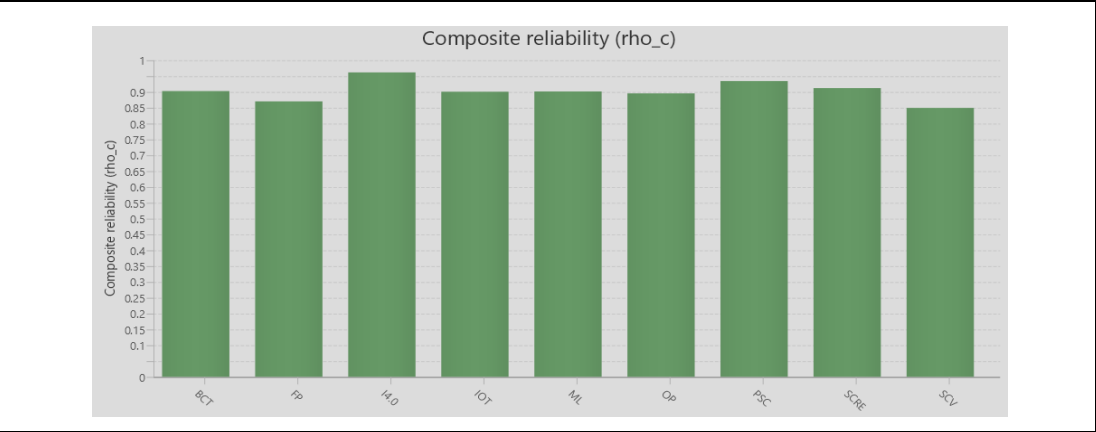
Table 6 - SEM results for measurement items and reliability indices

Variable	Items	Loadings	Variance inflation factor	Cronbach's alpha	Composite Reliability	AVE
IoT	IoT1	0.778	2.157	0.863	0.962	0.645
	IoT2	0.803	2.270			
	IoT3	0.749	1.970			
	IoT4	0.805	2.854			
	IoT5	0.809	2.760			
ML	ML1	0.816	2.612	0.864	0.902	0.648
	ML2	0.791	2.555			
	ML3	0.838	2.742			
	ML4	0.800	2.509			
	ML5	0.778	2.422			
BCT	BCT1	0.868	3.005	0.865	0.903	0.651
	BCT2	0.774	2.454			
	BCT3	0.811	1.955			
	BCT4	0.798	2.370			
	BCT5	0.779	2.296			
SCRes	SCRes1	0.785	3.393	0.885	0.912	0.635
	SCRes2	0.806	3.563			
	SCRes3	0.857	2.711			
	SCRes4	0.808	2.450			
	SCRes5	0.760	2.780			
	SCRes6	0.761	2.213			
SCV	SCV1	0.864	1.760	0.733	0.850	0.655
	SCV2	0.835	1.653			
	SCV3	0.721	1.469			
	SCV4	0.704	2.023			
OP	OP1	0.865	2.708	0.844	0.896	0.683
	OP2	0.887	2.892			
	OP3	0.799	2.611			
	OP4	0.748	1.706			
FP	FP1	0.816	2.158	0.800	0.870	0.629
	FP2	0.860	2.508			
	FP3	0.829	1.910			
	FP4	0.952	1.402			

Source: The authors themselves.

During the first crucial step of our analysis, we focused our attention on assessing Composite Reliability (CR) to measure the internal strength of each latent construct as shown in figure 2. The results, presented in the table above, demonstrate that Composite Reliability significantly exceeds the conventional threshold of 0.70 for all constructs. These high scores confirm robust internal consistency of our measures, reinforcing thus our confidence in the quality of the constructs evaluated.

Figure 2 - Composite reliability diagram

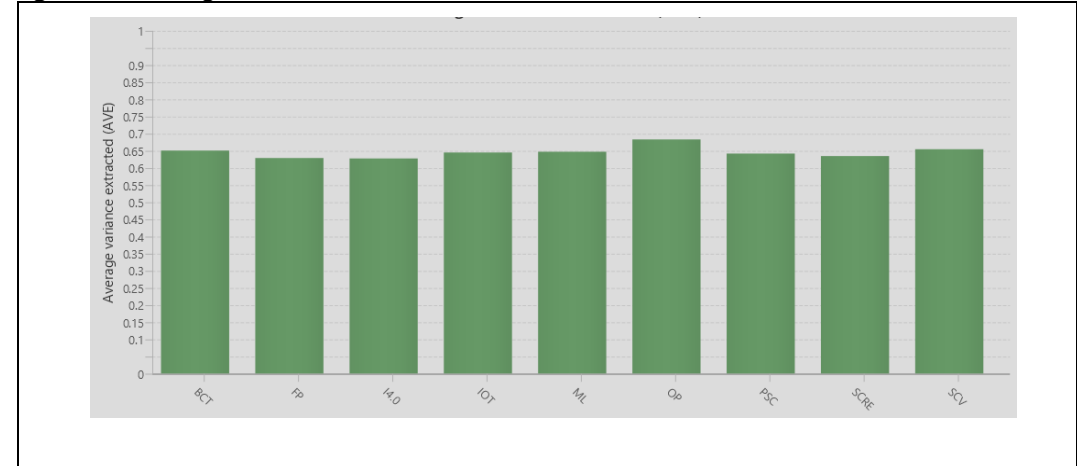


Source: The authors themselves.

To assess the internal consistency of our constructs, we also calculated the Cronbach index (Cronbach's Alpha). The results, presented in table 5, demonstrate that the Cronbach index far exceeds the established threshold of 0.70, thus confirming robust internal consistency for all the constructs evaluated. These high scores reinforce the reliability of our measures and contribute to the overall validity of our model.

Continuing with our evaluation of measurement models, we look at Average Variance Extraction (AVE) for each latent construct. AVE, representing the proportion of variance captured by measurement items relative to measurement error, provides crucial insights into the convergent validity of constructs and is represented in figure 3. The AVE values presented in table 5 confirm robust convergent validity, exceeding the recommended threshold of 0.50.

Figure 3 - AVE diagram



Source: The authors themselves.

To complete our assessment, we examined factor loadings and the variance inflation factor (VIF). High factor loadings, exceeding the threshold of 0.70, indicate a substantial contribution of the items to the measurement of the latent construct. Additionally, the VIF is examined for any indication of severe multicollinearity, with a cutoff value generally set at 10.

These analyzes strengthen the validity and stability of our measures, thereby laying a solid foundation necessary for subsequent interpretation and discussion of the results.

Table 7 presents the values of R^2 , Q^2 and F^2 , providing an in-depth assessment of the explanatory and predictive power of the model. The R^2 , measuring the proportion of variance explained, display robust values of 0.742, 0.981 and 0.975, demonstrating a solid ability of the model to explain the relationships between variables (Chin, 1998).

The R^2 values for OP (0.981) and FP (0.975) are exceptionally high. While this demonstrates strong explanatory power, such values may also indicate conceptual overlap between performance constructs and their antecedents, or common method variance inherent to self-reported data. We therefore caution against overinterpreting these coefficients. Future research should replicate our model using objective performance metrics and larger, more diverse samples.

Effect size is estimated using Q^2 , calculated as: $Q^2 = R^2 \times (1 - (1/F^2))$. In our study, the calculated effect size values amount to 0.732, suggesting a moderate relationship, while the coefficients of 0.960 and 0.949 indicate stronger relationships.

Finally, the evaluation of the predictive capacity of the model is carried out using F^2 for all the observed variables. These effect size and prediction indicators provide an in-depth understanding of the robustness of the proposed model. The results suggest that the model demonstrates significant ability to explain and predict relationships between the variables studied, thereby strengthening the validity and reliability of the conclusions drawn from this study.

Table 7 - Quality and practical utility of our research model

Construction	R^2	Q^2	F^2 compared to	
			SCRes	SCP
I 4.0	-	-	0,158	0,142
SCRes	0,742	0,732		
OP	0,981	0,960		
FP	0,975	0,949		

Source: The authors themselves.

Following Cohen's (1988) guidelines, the f^2 values for I4.0→SCRes (0.158) and I4.0→SCP (0.142) indicate small to medium effects, while the Q^2 values for SCRes (0.732), operational performance (0.960), and financial performance (0.949) are all well above zero, confirming that the model has satisfactory predictive power. We have also interpreted our results conservatively, staying within the bounds of our data. For instance, we do not claim that I4.0 "guarantees" resilience or performance ; rather, we state that I4.0 adoption explains a certain proportion of variance in our sample.

As an initial test of discriminant validity, we applied the Fornell-Larcker criterion. This involved verifying that the square root of the AVE for each construct was greater than the construct's correlations with all other constructs. The table 8 presents the detailed results of this comparison.

Table 8 - Test of discriminant validity (The Fornell-Larcker criteria)

Items	BCT	FP	I4.0	IoT	ML	OP	SCP	SCRes	SCV
BCT	0.807								
FP	0.642	0.793							
I4.0	0.786	0.751	0.792						
IoT	0.753	0.627	0.782	0.803					
ML	0.757	0.738	0.784	0.748	0.805				
OP	0.754	0.756	0.671	0.746	0.718	0.827			
SCP	0.659	0.787	0.673	0.747	0.665	0.790	0.821		
SCRes	0.551	0.643	0.665	0.542	0.534	0.656	0.561	0.797	
SCV	0.649	0.547	0.663	0.640	0.653	0.648	0.659	0.543	0.809

Source: The authors themselves.

Compliance with these criteria provides additional assurance regarding the ability of our measures to effectively discriminate between constructs, thereby strengthening the overall validity of our measurement framework. The values in the table indicate that the discriminant validity of the measurement model is acceptable, confirming the ability of the constructs to be distinguished from each other according to the Fornell-Larcker criterion.

Table 9 - Ratio Hetrotrait-Monotrait (HTMT)

Items	BCT	FP	I4.0	IoT	ML	OP	SCP	SCRes	SCV
BCT									
FP	0.715								
I4.0	0.842	0.784							
IoT	0.625	0.647	0.710						
ML	0.656	0.701	0.775	0.614					
OP	0.734	0.900	0.821	0.730	0.664				
SCP	0.745	0.896	0.823	0.701	0.703	0.747			
SCRes	0.355	0.274	0.367	0.332	0.265	0.280	0.285		

SCV	0.511	0.630	0.665	0.688	0.458	0.753	0.715	0.343
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Source: The authors themselves.

To provide a more rigorous test of discriminant validity, we additionally calculated the Heterotrait-Monotrait ratio of correlations (HTMT) following Henseler *et al.* (2015). As shown in Table 9, all HTMT values are below the conservative threshold of 0.85.

Turning to the HTMT results presented in Table 9, we find that the highest value, 0.900, occurs between operational performance (OP) and financial performance (FP). Although this figure marginally exceeds the conservative threshold of 0.85, it remains within the upper bound of the more permissive 0.90 criterion advocated by Hair *et al.* (2019). This outcome is theoretically justifiable. OP and FP are conceptually intertwined subdimensions of the broader supply chain performance construct. As Henseler *et al.* (2015) point out, HTMT ratios approaching 0.90 may still be acceptable when constructs share substantial empirical and conceptual overlap. We nonetheless recognize this as a limitation and propose that future investigations treat OP and FP as a unified second-order construct. Crucially, all other HTMT values lie well beneath the 0.85 benchmark. The value between I4.0 and SCRes is 0.367, between SCV and SCRes is 0.343, and between I4.0 and SCV is 0.665. This affirms satisfactory discriminant validity across the remainder of our measurement model.

All other HTMT values, including those involving Industry 4.0 (I4.0), supply chain resilience (SCRes), supply chain visibility (SCV), and supply chain performance (SCP), are well within the 0.85 limit. For example, HTMT between I4.0 and SCRes is 0.367, between SCV and SCRes is 0.343, and between I4.0 and SCV is 0.665. These results confirm that each construct in our model is empirically distinct from the others, thereby addressing the limitations of the Fornell-Larcker criterion and aligning with current methodological best practices.

4.3 Estimation of parameters and testing of proposed hypotheses

To test the hypotheses with the structural model, we graph the relationships between the studied variables using the PLS-SEM analysis diagram shown in Figure 4. This diagram provides a visual representation of the pathways and connections between the different constructs, highlighting the directions and intensities of the relationships identified during our analysis. By looking closely at this figure, we can better understand the impact of the adoption of I4.0 on supply chain resilience. Notably, it highlights the moderating role played by SCV in the relationship between I4.0 adoption and SCRes. This finding suggests that SCV acts as a crucial moderator, moderating the effect of I4.0 on supply chain resilience. The respective path coefficients and p-values to test the relationship of the hypotheses.

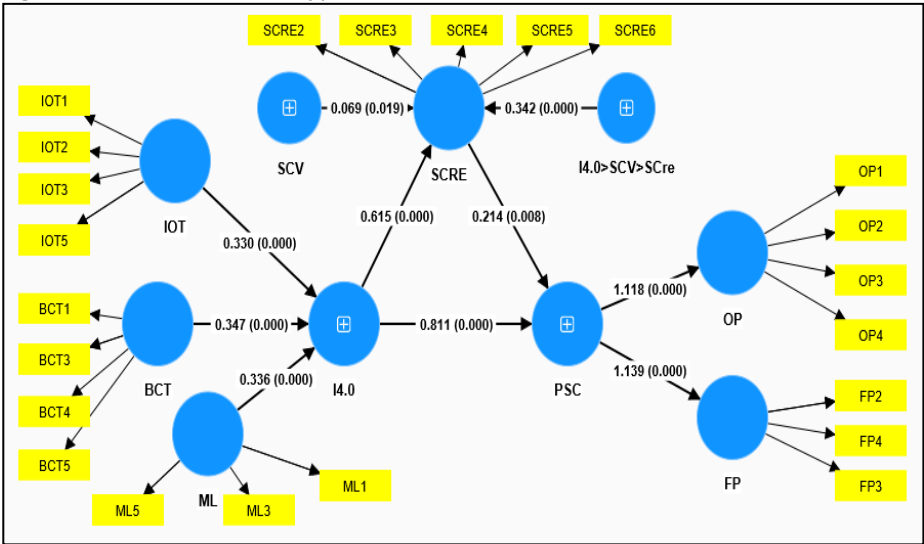
Detailed analysis of the results will assess the strength and direction of relationships between variables, providing crucial insights to validate our research hypotheses. The table 10 below presents the results related to the direct analyzes of the hypotheses (H1, H2a, H2b, H3), as well as other analysis results that do not include mediation or moderation.

Table 10 - Analysis of the proposed hypotheses

Hypothesis	Effects	β	p-value	Results (acceptance/reject)
H1	I4.0 →SCP	0,811	0,000	rejection of the null hypothesis
H2a	I4.0 →SCRes	0,615	0,000	rejection of the null hypothesis
H2b	SCRes→SCP	0,214	0,008	rejection of the null hypothesis
H3	SCV→SCRes	0,069	0,019	rejection of the null hypothesis

Source: The authors themselves.

Figure 4 - Estimation of the hypothetical model



Source: The authors themselves.

The results indicate a significant and positive impact from I4.0 to SCP ($\beta = 0.811$, $p\text{-value} = 0.000$), thus providing support for hypothesis H1. Likewise, the results demonstrate a positive relation between I4.0 and SCRes ($\beta = 0.615$, $p\text{-value} = 0.000$), leading to rejection of the null hypothesis and support for hypothesis H2a. Furthermore, SCRes presents a significant and positive association with SCP ($\beta = 0.214$, $p = 0.008$), supporting hypothesis H2b. Regarding the moderating role of SCV, the results show that the direct influence of SCV on SCRes is positive and statistically significant ($\beta = 0.069$, $p = 0.019$), thus supporting hypothesis H3.

We next explore the results of mediation (H2) and moderation (H4) to provide additional insight into the underlying mechanisms of the relationships studied. Table 11 presents the detailed results of mediation and moderation in our model. Hypothesis 2, which tests the mediating role of SCRes in the relationship between I4.0 and SCP, is formulated by combining hypotheses H2a and H2b.

Table 11 - Tests for the presence of a mediation and/or moderation effect

Hypothesis	Null hypothesis	β	P-value	Results (acceptance/reject)
H2	I4.0 $\rightarrow$ SCRes $\rightarrow$ SCP	0,131	0,008	rejection of the null hypothesis
H4	I4.0 $\rightarrow$ SCV $\rightarrow$ SCRes	0,342	0,000	rejection of the null hypothesis

Source: The authors themselves.

The results of this study support Hypothesis 2 ($\beta = 0.131$, $p = 0.008$), confirming that SCRes mediates the relationship between I4.0 and SCP. Furthermore, the results support Hypothesis 4 ($\beta = 0.342$, $p < 0.001$), confirming that SCV positively moderates the relationship between I4.0 and SCRes.

These results reinforce the idea that SCRes plays a critical mediating role in the relationship between I4.0 adoption and SCP, thus validating the importance of resilience as an underlying mechanism. Furthermore, the results of H4 suggest that SCV acts as a positive moderator in the relationship between I4.0 and SCRes, thus highlighting the crucial role of visibility in amplifying the effect of I4.0 technologies on supply chain resilience. These findings provide valuable insights for practitioners seeking to maximize the benefits of adopting I4.0 in their supply chain, with a focus on improving both resilience and visibility.

5 LIMITATIONS OF THE INVESTIGATIONS

This study has several limitations that should be acknowledged in addition to the exclusion of certain Industry 4.0 technologies. First, the sample size is relatively small ($n=81$). While post-hoc power analysis indicates that this sample meets the minimum required for PLS-SEM ($n=70$; Hair *et al.*, 2017) and variance inflation factors are within acceptable ranges, findings may not generalize to the broader population of Tunisian firms. Second, the cross-sectional design captures relationships at a single point in time, preventing causal inference. Reported associations should therefore be interpreted as correlational. Third, the use of self-reported survey data introduces potential social desirability bias and common method variance, although Harman's single-factor test indicates that common method bias is not a major concern. Fourth, only three I4.0 technologies

(IoT, ML, BCT) were examined; other technologies such as artificial intelligence, digital twins, and big data analytics may further influence supply chain performance, resilience, and visibility. Fifth, the single-country context of Tunisia limits applicability to other emerging economies with different industrial structures, regulatory environments, and technological maturity levels. Future research should address these limitations by using larger, more diverse samples (e.g., $n > 200$), longitudinal designs (e.g., repeated measures over 12–24 months), multi-country comparisons (e.g., Tunisia, Morocco, and Egypt), and broader sets of I4.0 technologies. Despite these limitations, our findings provide meaningful theoretical and practical contributions, as discussed below.

6 DISCUSSION

6.1 Results discussion

This subsection has two parts. First, we highlight the impact of I4.0 adoption on SCRes and the role of SCV in this relationship. I4.0 not only directly improves performance; it equips companies with tools to enhance resilience, and it is this enhanced resilience that directly drives performance gains. Investing in I4.0 enhances supply chain resilience, which in turn drives performance gains. Without a deliberate strategy to strengthen resilience, the performance benefits of I4.0 adoption remain suboptimal.

SCV is a moderator and not just a direct driver. SCV determines how effectively a company can convert its I4.0 technological capabilities into tangible resilience. It does not simply make the supply chain more resilient on its own; instead, it amplifies or strengthens the positive impact that I4.0 has on resilience. SCV amplifies the translation of I4.0 technological capabilities into achieved supply chain resilience. Its role is not merely additive but multiplicative; it amplifies the positive effect of I4.0 on resilience. While I4.0 provides the data-generating infrastructure, SCV constitutes the information-processing and decision-making layer. The efficacy of the infrastructure is wholly contingent upon the clarity and integration of this layer. High-quality SCV ensures the data produced by I4.0 is actionable, thereby maximizing its contribution to resilience.

The strength of the relationship between I4.0 investment and resilience is directly determined by the level of supply chain visibility. The efficacy of I4.0 investments in bolstering supply chain resilience is highly dependent on the pre-existing level of visibility. Firms with low visibility experience diminished returns, as the technological potential remains untapped. Conversely, firms with high visibility can fully actualize this potential, achieving a significantly more resilient supply chain.

Second, we discuss the impact of supply chain resilience on operational and financial performances. SCRes does not directly boost performance; instead, it first reduces supply chain risk, and this risk reduction subsequently leads to improved performance. Supply chain resilience functions as a critical risk mitigation mechanism. This occurs through a dual mechanism: (1) reducing the probability of disruption through proactive measures (e.g., supplier diversification), and (2) minimizing the negative impact when disruptions are unavoidable through reactive capabilities (e.g., flexible logistics networks).

Thus, resilience acts as a comprehensive risk dampener across the disruption lifecycle. When risk is lower and better managed, the company operates in a more stable and predictable environment, which is a direct driver of performance. Operationally, this means higher on-time delivery, consistent product quality, and greater customer satisfaction. Financially, it translates to lower costs (by avoiding emergency expenditures), protected revenue (by preventing stock-outs), and stabilized profit margins.

Around 2018, with the growth of domestic demand, Firm A began to shift its focus to the China market. Initially, the domestic market was regarded as a secondary channel for exporting surplus products or slightly adjusted export products. However, the company soon faced fierce competition from local digital native brands, which are more flexible, keep up with the trend and can quickly respond to the changing preferences of consumers. By 2022, Firm A realized that its standardized production mode was increasingly mismatched with the fast-paced and price-sensitive domestic market, which led to the strategic contradiction discussed in this study.

6.2 Comparison with prior studies

Our finding that Industry 4.0 adoption positively influences supply chain performance corroborates Qader *et al.* (2022), who documented similar effects, as well as Dubey *et al.* (2020), who demonstrated that digital technologies enhance operational agility. Our study does not claim to introduce the visibility moderation effect; rather, it extends Qader *et al.* (2022) by demonstrating

that this moderation effect holds, and may be even more pronounced, in the Tunisian context. We attribute this to the elevated degree of information asymmetry and fragmented logistics characteristic of Tunisian supply chains, which amplify the value of visibility mechanisms. This context-specific finding represents our primary empirical contribution. With respect to the moderating role of supply chain visibility, our findings are consistent with the theoretical predictions of information processing theory. We also recognize certain discrepancies with existing literature. Specifically, whereas some studies reported no significant moderating effect of visibility under conditions of low environmental uncertainty, our results confirm a robust moderating effect. We attribute this divergence to the elevated degree of information asymmetry characteristic of Tunisian supply chains, which amplifies the value of visibility mechanisms. Regarding external pressures, our results support the institutional theory framework advanced by Dubey *et al.* (2020) but further contribute a novel insight, namely that mimetic pressures exert a stronger influence on Industry 4.0 adoption than coercive pressures, a distinction not previously documented. In sum, this comparison with prior work underscores our unique contributions, specifically the original integration of Information Processing Theory, the Resource Based View, and Institutional Theory, the identification of supply chain visibility as a critical moderator, and the empirical validation of these relationships within the under researched context of North Africa.

6.3 Managerial implications

Beyond its theoretical value, this research offers an actionable plan for Tunisia's industrial evolution, showing how a strategic focus on Industry 4.0-driven resilience and visibility can directly boost the private sector's competitiveness, strengthen the national economy, and ensure a more prosperous position in the global market. For Tunisian companies, the study demonstrates that investing in I4.0 is not only a technology project but also a strategic project to build a resilient and visible supply chain, which is the true driver of performance. Adopting this strategy allows Tunisian firms to transcend their subcontractor status and become vital strategic partners in global supply chains. Tunisia's industrial sector presents a contrasting picture of I4.0 maturity. Pioneering and advanced companies demonstrate the tangible benefits of adoption, offering a clear path for others to follow. The primary challenge and step to widespread transformation lies in overcoming the critical skills shortage and making advanced technological solutions accessible to the SME sector.

Given the high and comparable loadings for all three technologies (above 0.77), managers should adopt them as a complementary bundle rather than prioritising one over another. Second, the moderation effect of SCV ($\beta = 0.342$) demonstrates that visibility amplifies the impact of I4.0 on resilience. Consequently, firms should implement visibility-enhancing systems (e.g., real-time dashboards, shared data platforms) concurrently with I4.0 adoption, not as a later addition. Third, to track progress, we recommend monitoring two KPIs derived from our measurement items: disruption recovery time (based on SCRes items) and frequency of real-time data sharing (based on SCV items).

For policymakers, facilitating this transition is a national imperative. It is an investment in constructing a more robust, resilient, and prosperous future of national economic. Creating a national industrial strategy (Tunisia 4.0) that explicitly links I4.0 adoption to supply chain resilience and export competitiveness can help to make national vision clearer, aligns efforts, and attracts the right kind of foreign investment.

To accelerate modernization of the industrial base, policy makers should deploy a suite of financial instruments including tax credits, direct grants, and concessional loans. These should be strategically allocated to firms investing in 1) Digital Transformation and especially in the acquisition and implementation of core I4.0 technologies. 2) Visibility infrastructure and projects that demonstrably enhance end-to-end supply chain transparency and 3) Supply Chain Resilience and initiatives that enhance resilience (e.g., supplier diversification programs, inventory buffer stock for critical industries). Fund applied research projects between universities and companies focused on solving real-world supply chain challenges using I4.0. Promote the formation of industrial clusters where companies can share best practices and resources.

It is crucial to drive innovation by funding university-industry partnerships that tackle real-world supply chain problems with I4.0 technologies. Additionally, foster industrial clusters to create ecosystems where companies can collaboratively share knowledge, resources, and build synergies.

7 CONCLUSION

In this study, we set out to understand how Industry 4.0 technologies affect supply chain performance in Tunisian companies, paying special attention to two mechanisms: the mediating role of supply chain resilience and the moderating role of supply chain visibility. The results support all six hypotheses. First, we found a strong positive relationship between I4.0 adoption and supply chain performance ($\beta = 0.811$). Second, I4.0 also strengthens supply chain resilience ($\beta = 0.615$), and resilience itself improves performance ($\beta = 0.214$). Importantly, resilience partially mediates the link between I4.0 and performance ($\beta = 0.131$), meaning that part of I4.0's performance operates through enhanced resilience. Third, visibility directly enhances resilience ($\beta = 0.069$) and, more interestingly, moderates the I4.0–resilience relationship ($\beta = 0.342$): when visibility is higher, the positive effect of I4.0 on resilience becomes stronger.

From a theoretical standpoint, our findings confirm the integrated framework developed by Qader *et al.* (2022). The mediation effect (H2) confirms that resilience is a concrete mechanism through which I4.0 translates into better performance, while the moderation effect (H4) supports Information Processing Theory by showing that visibility reduces information uncertainty and asymmetry, thereby amplifying the impact of I4.0 on resilience. The contribution of this study lies in demonstrating that this integrated framework is generalizable to an African emerging economy, and in providing context-specific managerial and policy implications for the SME-dominated industrial sector of Tunisia. In other words, visibility is not merely another direct driver, it is a boundary condition that determines how effective I4.0 investments will be. Institutional Theory, although not directly tested here, offers a useful lens for future research on external pressures that push firms toward I4.0 adoption.

On the practical side, our path coefficients suggest three actionable guidelines for managers. First, treat I4.0 technologies as a complementary bundle IoT, machine learning, and blockchain work best together to maximise resilience gains. Second, do not delay visibility-enhancing systems; implement them at the same time as I4.0 adoption, because the moderation effect ($\beta = 0.342$) shows that visibility significantly amplifies I4.0's contribution to resilience. Third, use supply chain resilience as an intermediate performance metric. Tracking concrete indicators such as disruption recovery time and the frequency of real-time data sharing helps managers see whether their I4.0 investments are actually delivering tangible improvements.

This study has six main limitations. First, because we used a cross-sectional design, we can only capture relationships at one point in time, which means we cannot draw firm causal conclusions. Second, our data come from a single country (Tunisia) so we must be cautious about generalising the findings to other emerging economies. Third, we focused on just three Industry 4.0 technologies (IoT, machine learning, and blockchain); other promising ones like artificial intelligence, digital twins, or big data analytics were left out. Fourth, the use of self-reported survey data may introduce some social desirability bias. That said, future research can tackle these issues by adopting longitudinal designs, comparing multiple countries (for example, Tunisia, Morocco, and Egypt), including additional technologies, and using objective performance metrics. We have also deliberately avoided repeating material that is already covered elsewhere such as the PLS-SEM procedures or the measurement items. Five, given that the HTMT value between operational and financial performance reached 0.900, future studies might want to model these two dimensions as a single second-order construct of supply chain performance. Finally, because our study adapts the framework of Qader *et al.* (2022) rather than developing a new model, its theoretical contribution is primarily one of contextual validation and extension rather than framework development. Future research could advance theory by integrating additional theoretical lenses, such as Institutional Theory, and testing them empirically with dedicated measurement instruments.

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