International Journal of Knowledge and Innovation Studies
https://www.acadlore.com/journals/IJKIS

An ISM-Based Framework for Open Innovation Enablers Driving the Adoption of Industry 4.0 in Small Manufacturing Firms in Caribbean Small Island Developing States

Annusha Bridglal[1*], Kit Fai Pun[2]

[1] Arthur Lok Jack Global School of Business, Faculty of Social Sciences, The University of the West Indies, 3224 Mount Hope, Trinidad and Tobago

[2] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, The University of the West Indies, 3303 St. Augustine, Trinidad and Tobago

[*] Correspondence: Annusha Bridglal (annusha.bridglal@gmail.com)

Received: 07-03-2024 **Revised:** 08-26-2024 **Accepted:** 09-11-2024

Citation: A. Bridglal and K. F. Pun, "An ISM-based framework for Open Innovation enablers driving the adoption of Industry 4.0 in small manufacturing firms in Caribbean Small Island Developing States," *Int J. Knowl. Innov Stud.*, vol. 2, no. 3, pp. 155–178, 2024. https://doi.org/10.56578/ijkis020304.

Abstract: This study examines the role of Open Innovation (OI) in facilitating the adoption of Industry 4.0 (I4.0) technologies by small manufacturing enterprises in the non-energy sector of Caribbean Small Island Developing States (SIDS). These firms encounter significant challenges, including limited resources, inadequate infrastructure, and underdeveloped innovation ecosystems, which necessitate the adoption of tailored OI practices. A comprehensive literature review was conducted to identify the key enablers of OI, which led to the development of a conceptual framework. Insights gained from structured interviews with industry experts were used to assess the influence of these enablers on I4.0 adoption. Pairwise comparisons were employed to explore the interrelationships among these factors, culminating in the construction of a reachability matrix and a hierarchical model through Interpretive Structural Modelling (ISM) to analyse the dependencies and causal relationships among them. The study identified "Competitive Pressure," "Customer Pressure," and "Managerial Dynamic Capabilities" as the primary enablers driving OI and influencing the adoption of I4.0 technologies. Intermediate factors, such as "Digital Trust," "R&D Investment Capabilities," and "Collaborative Networks," were found to mediate the relationship between the primary enablers and the outcome of "Adaptation to Global Best Practices." Despite the fact that OI practices are often driven by external pressures, the adoption of I4.0 technologies was found to be strongly supported by managerial dynamic capabilities, highlighting the importance of both push and pull factors. The adaptation to global best practices is significantly shaped by managerial capabilities, competitive pressures, and customer demands. Furthermore, environmental scanning was identified as an essential tool for aligning managerial dynamic capabilities with market conditions, facilitating agile decision-making for technology adoption through collaboration. Strategic interventions to support intermediary factors are crucial for small firms to navigate external pressures, sustain innovation, and build internal capabilities for I4.0. The findings contribute to the development of a networked ecosystem framework, which offers a pathway to strengthening stakeholder alliances, implementing customer-centric open OI practices, and enhancing management effectiveness. It is concluded that the successful adoption of I4.0 technologies is achievable through strategic, managerial, and policy-driven frameworks that align with global standards and address competitive and customization demands.

Keywords: Open Innovation (OI); Industry 4.0 (I4.0); Caribbean Small Island Developing States (SIDS); Small manufacturers; Technology adoption; Managerial dynamic capabilities; Interpretive Structural Modelling (ISM)

1 Introduction

I4.0, also known as the Fourth Industrial Revolution, is transforming the manufacturing and industrial processes driven by advanced digitalisation. I4.0 integrates cyber-physical systems with advancing technologies such as artificial intelligence (AI), robotics, the Internet of Things (IoT), and automation. The goal of I4.0 is to enhance productivity, efficiency, and adaptability while enabling intelligent decision-making and customisation [1]. However, despite its transformative potential, I4.0 poses significant implementation challenges for small firms in developing economies. These include high costs, limited technology standardisation, interoperability issues, workforce reskilling needs, and ethical concerns [2, 3].

Traditional and outdated manufacturing processes are unable to foster industrialization in the current era of I4.0. In Caribbean SIDS, small firms are pivotal to national employment and export diversification [4]. Yet, they face substantial barriers to technological innovation, including financial constraints, knowledge gaps, and regulatory challenges [5, 6]. Limited innovation capacity among these firms restricts industrialisation and structural transformation, impeding economic growth in the region. Only 15% of firms in the Caribbean introduce innovations, with 59% willing but unable to do so due to cost, knowledge, and regulatory barriers [7, 8].

The concept of OI offers a promising paradigm for overcoming the systemic barriers to technological innovation [9]. OI is particularly pertinent in developing economies, where partnerships with universities, startups, and multinational corporations can drive knowledge exchange and innovation [10]. By integrating internal and external knowledge, OI can facilitate solutions to resource, regulatory and technological limitations. For Caribbean SIDS, small firms are vital in advancing OI through capability-building initiatives [11]. However, the success of these efforts hinges on fostering flexible leadership and enabling effective knowledge exchange [12].

OI holds significant potential to mitigate risks and costs, expand market access, and foster technological innovation through collaborative learning [13]. However, its success depends on the interplay of enabling factors, which the literature classifies in different ways. These factors are often grouped into internal elements—such as entrepreneurial and managerial orientation, organisational culture, and innovation climate—and external influences, including market conditions and network positioning [12]. Notably, these factors are increasingly seen as interrelated. For example, managerial orientation shapes actor networks, which in turn can either foster or hinder OI in small firms [14].

The complex interrelationships among enabling factors for OI that drive I4.0 adoption remain critical yet poorly understood, particularly in the context of Caribbean SIDS. This study addresses this gap through a multi-faceted approach. First, it employs OI interventions in I4.0 projects within developing economies to identify and validate critical enablers for small firms. Second, it is one of the first studies to examine OI adoption from both the manufacturing sector and small firm perspectives in the context of Caribbean SIDS. Third, it applies ISM to analyse and rank the relationships among these enablers, illustrating how they can support small firms in the manufacturing industry through OI practices. Three (3) Research Questions (RQ) are put forward. These are:

RQ1: What are the significant enablers of OI?

RQ2: What are the hierarchical levels of these enablers?

RQ3: How do the enablers of OI interact to facilitate I4.0 technology adoption?

The study seeks to explain the interrelationships among OI-enabling factors and their impact on I4.0 adoption by small firms in the manufacturing sector of Caribbean SIDS. It employs a Multiple-Criteria Decision-Making (MCDM) approach, where ISM is used to determine direct and indirect relationships among OI-enabling factors.

The paper is structured as follows: Following the introduction section, Section 2 examines the relevant literature on OI, I4.0 adoption, and the profile of small manufacturing firms in the non-energy sector of Caribbean SIDS. Section 3 discusses the identification and selection of key enabling factors for OI, followed by Section 4, in which the methodology is discussed. Section 5 presents an overview of the methods and their implementation. Section 6 discusses the findings, followed by Section 7, which outlines implications (practical and managerial) and the conclusions.

2 Literature Review

The literature has been reviewed from the perspectives of OI and I4.0 in applications for small firms in developing economies. A summary of recent research on OI and I4.0 technology adoption is given in Appendix 1, and respective core areas of research are addressed below.

2.1 OI

OI is defined as a paradigm in which firms leverage both internal and external knowledge to advance their technology and business models, thereby improving business value and competitive advantage [9, 15, 16]. This approach facilitates the inflow and outflow of knowledge to accelerate internal innovation while expanding markets for external use [15]. OI involves two key processes: inbound innovation (sourcing and acquiring external knowledge) and outbound innovation (disseminating and selling internal knowledge) [17, 18]. By forming collaborative relationships with organisations such as universities, researchers, and even competitors, firms can effectively exploit innovation [19]. This dynamic is particularly relevant in the era of I4.0, where big data ecosystems and various organisational modes enable faster and more extensive information sharing with external actors, accelerating the exchange of knowledge and business value [20].

OI can lead to improved products and services, competitive advantage, and financial benefits by integrating external knowledge into internal research and development (R&D) processes [21]. As a multi-dimensional concept, the impact of OI varies across firms, with success relying on specific organisational and environmental factors. Effective implementation of OI requires strategic planning, such as selecting appropriate collaboration partners, defining phases of the innovation process, and choosing the right tools to support openness [22]. Firms can adopt different strategies based on their characteristics and inter-organisational exchange mechanisms, such as innovation seeker, provider, intermediary, or open innovator [23].

The closed innovation model, which dominated the 20th century through companies like General Electric and Bell Labs, was effective for driving significant technological advancements [9]. However, increased mobility of knowledge workers and the rise of private venture capital made it more challenging for firms to control proprietary knowledge, leading to the emergence of OI. The inability to consistently profit from internal R&D investments, especially as employees left to form startups, spurred the shift toward a more collaborative and OI approach [9, 24].

OI fosters a decentralized, cooperative approach that enhances innovation speed and agility. This emphasis on external collaboration—particularly in sharing market and customer knowledge—has become essential for businesses striving to remain competitive in the digital age. By leveraging both internal and external knowledge, OI allows companies to innovate in ways that reduce costs, speed up market entry, increase differentiation, and create new revenue streams [25].

Moreover, OI has profound implications for I4.0, which is characterized by automation and digitalization. Firms that integrate OI into their digital innovation processes can innovate more rapidly than their competitors who do not [25]. OI also enables the effective use of external ideas and technologies, extending collaboration beyond technology sharing to include market, customer, and business model knowledge—critical for innovation success [25].

Looking ahead, OI is expected to be a key driver of innovation in developed economies, especially as emerging technologies like blockchain, digitalization, and genomic editing continue to evolve [10]. Additionally, the United Nations Sustainable Development Goals (SDGs) for 2015-2030 are expected to serve as a catalyst for OI initiatives [10]. However, small to medium enterprises (SMEs) in developing economies face significant challenges in implementing OI. These include limited resources, high infrastructure costs, vulnerability to external shocks, and dependence on foreign investment [26].

2.2 I4.0

I4.0, driven by advanced technologies such as the IoT, AI, and cyber-physical systems, presents developing countries with opportunities to enhance their industrialization and global competitiveness. These technologies can significantly improve productivity, reduce environmental impacts, and drive economic growth, offering the potential to secure a larger share of the global manufacturing value chain [27]. Additionally, I4.0 can support SDGs and enable circular economy practices, fostering innovative and diversified business models [28]. Contrary to concerns about automation-induced job losses, studies suggest that these technologies may create more jobs than they replace [29]. However, while these advancements are promising, the social benefits of I4.0 in developing countries remain less pronounced [30].

Challenges to the adoption of I4.0 technologies in developing countries are significant. Many firms face constraints such as inadequate digital strategies, resource limitations, and underdeveloped technological infrastructure [3, 29]. These barriers are exacerbated by a lack of skilled labour, insufficient expertise, and the absence of coordinated national policies [3, 31]. Smaller firms and those without dedicated R&D capabilities face greater difficulties in integrating I4.0 technologies [31]. Without addressing these challenges, there is a risk that developing countries may experience slower industrialization, further widening global inequalities [32].

To overcome these barriers, developing countries require tailored strategies. National science, technology, and innovation policies, along with international collaborations, are essential to building a robust industrial base and preparing for rapid technological advancements [3, 29]. Investments in R&D, particularly in high-tech sectors, can enhance readiness for I4.0 transformations [31]. Strengthening education and training initiatives is also critical to addressing skill shortages and equipping workforces with the capabilities required for digital transformation [31]. Moreover, enabling factors such as managerial, operational, and technological readiness, financial capability, strategic vision, and top management support are crucial for the successful adoption of I4.0 in developing economies, as they help organisations overcome challenges, enhance flexibility, and achieve competitive advantages [33, 34].

2.3 Small Firms in Caribbean Non-energy Manufacturing Sector

Small firms, particularly Micro, Small, and Medium-sized Enterprises (MSMEs), form the backbone of the economic landscape in Caribbean SIDS [4]. Despite their importance, they face substantial structural and operational barriers that hinder growth, innovation, and resilience. The Caribbean Development Bank (CDB) highlights the lack of uniform definitions for MSMEs across the region, complicating policymaking and resource allocation. A proposed standardized classification—micro (1–5 employees), small (6–15 employees), and medium (16–50 employees)—aims to address this issue and align support mechanisms with the unique scale of Caribbean businesses [35].

Globally, the adoption of I4.0 technologies poses significant challenges for small firms in developing economies. Kumar et al. [2] identify financial constraints, insufficient IT infrastructure, workforce limitations, and fear of implementation failure as key barriers. These issues are compounded by inadequate regulatory frameworks, as noted by Bogoviz et al. [36], which underscores the need for targeted policies to foster digital transformation.

In the Caribbean context, small firms have struggled to adopt digital solutions, particularly during the COVID-19 pandemic, due to limited resources and strategic gaps in digitalization [7]. This is further exacerbated by small market size, which restricts access to skilled labour and critical inputs, and financial constraints, with 80% of firms citing funding challenges post-pandemic [7]. In comparison, firms in developed economies benefit from better awareness and higher adoption rates of advanced technologies [37].

Firm size also plays a critical role in innovation capacity. Larger firms in the Caribbean are more likely to innovate due to higher per-employee investments and resource availability. Mohan et al. [6] found that innovation expenditure increases the probability of technological advancements by approximately 50%, while smaller firms face disproportionate cost and knowledge barriers. Notably, foreign-owned firms are less likely to innovate locally, relying on innovations from parent companies. This reflects structural challenges such as weak intellectual property protections and a preference for low-risk operational expansions in the region [6].

Addressing these barriers consequently requires a multi-pronged approach as highlighted by Acevedo et al. [7]. Governments and multilateral institutions must prioritize policies that address market failures, structural constraints, and tailored support for opportunity-driven and necessity-driven entrepreneurs, alongside public investments in human capital, IT infrastructure, and innovation funding [7, 38]. Expanding market integration and skilled labour retention policies can further enable growth. By fostering an enabling environment, stakeholders can empower MSMEs to drive innovation, resilience, and sustainable economic growth in the Caribbean.

3 Selection and Identification of OI Enabling Factors

A comprehensive literature review was undertaken on the studies of factors of OI in developing economies and I4.0 technology adoption. A keyword search of the titles and abstracts of references using search terms including "open innovation," "Industry 4.0," "technology adoption," "developing economies," "Caribbean SIDS," and "Interpretive Structural Modelling," was conducted. Search engines like Google Scholar, Emerald, ProQuest, Mendeley Reference Manager, Scopus, and IEEE Xplore were utilized. Information about the article (author, location, year of publication, title, DOI) and information about the study (study type, participant recruitment / selection / allocation, level of evidence, study quality) were extracted. Studies were screened based on data that was relevant to answering the research questions according to several parameters, including:

1) Whether the quality of the article fulfilled the conditions of peer-review, accuracy, currency and objectivity.

2) Whether the research was conducted from a developing region/country perspective.

3) Whether the industry focus was on small manufacturing firms in the non-energy sector.

4) Whether the article addressed OI as a concept, theory or proposition in a manner that was substantiative enough to be analysed from the assessment of its enabling factors.

5) Whether technology adoption (specifically, I4.0 technology adoption) was addressed as a concept that was associated with OI.

6) Whether there was an observed interaction/relationship between OI and technology adoption.

7) Whether the methodology was valid, reliable and robust.

8) Whether the concepts were sufficiently examined to prescribe practical implications.

Table 1. Selected factors of Open Innovation (OI) and Industry 4.0 (I4.0) technology adoption

No.	Factor and Code	Description	References
01	Dynamic Managerial Capabilities	The abilities of managers to sense opportunities and threats, seize them, and reconfigure organisational resources and processes in response to changing environments. It highlights the leadership's ability to adapt, learn, and pivot in dynamic, uncertain environments.	[40]
02	Business Model (Oriented to Openness)	The design and structure of an organisation's approach to value creation, delivery, and capture with an emphasis on openness. This openness often relates to external collaborations, partnerships, sharing of intellectual property, co-creation with customers, and leveraging external networks for innovation.	[19, 42]
03	Government Support Mechanisms	The combined influence of governmental roles, policies, and initiatives that enable and promote organizational growth, innovation, and technology adoption.	[41, 45, 46]
04	Ecosystems for Technology Transfer	The network of organisations, institutions, and processes that enable the movement of technology from creators (e.g., research institutions, universities) to users (e.g., businesses, manufacturers).	[48]
05	Collaborative Networks	The cooperative relationships, partnerships, and structured or informal networks among diverse stakeholders, including businesses, organisations, academia and individuals.	[19, 42, 44, 45]
06	R&D Investment Capability	The ability of an organisation to strategically allocate financial and non-financial resources toward R&D initiatives and to effectively leverage these investments to drive innovation, improve processes, and develop competitive products or services.	[39, 40]
07	Competitive Pressure	Intense competition that compels organisations to innovate faster and more effectively to differentiate themselves.	[43]
08	Customer Pressure	Increasing demand for personalized solutions, higher quality, and sustainability by customers which encourage firms to engage with external partners, such as suppliers, universities, or startups, to co-create value and improve offerings.	[43]
09	Digital Transformation	The strategic integration of digital technologies into all areas of an organisation, fundamentally changing how it operates, delivers value to customers, and competes in the market.	[78]
10	Digital Trust	The confidence stakeholders place in the integrity, reliability, and security of digital technologies, platforms, and processes.	[78]
11	Internal Knowledge Flows	The exchange, management, and utilization of knowledge within an organization.	[19, 41-44]
12	Adaption to Global Best Practices	The ability of organisations to identify, incorporate, and tailor internationally recognized standards, methods, and processes to fit local contexts and operational needs.	[79, 80]
13	External Knowledge Flows	The information, insights, and expertise that an organisation acquires from external sources such as customers, suppliers, competitors, academic institutions, research organisations, industry best practices, and public databases.	[39, 40]

A total of forty-eight factors were initially identified from the literature review related to OI and I4.0 technology adoption (Appendix 1). To reduce redundancy and address conceptual overlap, several constructs were merged into unified factors, reflecting their complementary nature and shared dimensions.

For example, “R&D Spending” [39] and “R&D Capability” [40] were combined into one factor “R&D Investment Capability”, as both terms broadly encapsulate the dimension of innovation related to investment in and the capacity for conducting R&D activities.

Similarly, “Knowledge Management” [41], “Knowledge Flows Across Organisational Boundaries” [39, 42], “Knowledge” [43], and “Knowledge Flows” [44], were merged into the factor “Internal Knowledge Flows”. These terms collectively describe the systems, processes, and practices that facilitate the creation, sharing, and application of knowledge within and across individuals, teams, and departments.

In addition, “Government Role” [41], “Public Policy Support” [45], “Government-Supported Initiatives” [46], and “Policy Development” [47], were consolidated into a single factor, “Government Support Mechanisms”. These constructs overlap in their indicators, such as the provision of government funding, the establishment of supportive regulatory frameworks, and the implementation of innovation-focused programs.

Lastly, “Cooperation” [9, 42], “Actor Networks” [45], “Partnerships and Networks” [46], “Cooperation Between Academia, Industry, and Governments” [48], and “Business Partnerships” [44] were unified under the factor “Collaborative Networks”. These terms describe the collaborative relationships formed through actor networks and partnerships, whether business-oriented or otherwise. Actor networks and business partnerships are integral components of broader collaborative ecosystems, further justifying their consolidation.

Furthermore, “Competitive and Customer Pressure” [43], was denoted as two separate factors: “Competitive Pressure” and “Customer Pressure”. While competitive pressure typically refers to the external drive exerted by rivals in the market, pushing firms to adopt new technologies or practices to maintain their competitive edge, customer pressure pertains to the expectations and demands of customers, which directly influence a firm’s value proposition and operational priorities.

To refine the list of factors for relevance to the Caribbean’s non-energy sector, two selected study participants, one from academia and one industry expert, evaluated the constructs. The Delphi technique was employed to achieve consensus among the experts. As a result, thirteen significant factors were retained to represent the enablers of OI in small manufacturing firms and I4.0 technology adoption, as illustrated in Table 1.

4 Methodology

Decision-making techniques are extensively researched and utilized across numerous disciplines. Among these, MCDM stands out as a valuable tool for analysing and prioritizing criteria in complex situations. Its versatility has made it particularly useful in fields such as innovation research, where it aids in ensuring effective and systematic decision-making processes.

4.1 Use of MCDM Approach and Techniques

MCDM is a powerful approach that integrates both quantitative and qualitative factors, enabling decision-makers to evaluate, rank, or categorize alternatives across various criteria. It is effective in addressing complex and conflicting objectives, making it highly valuable for informed decision-making [49, 50].

MCDM techniques have been extensively utilized in innovation contexts to improve decision-making and outcomes. For example, in outbound open OI, MCDM has been applied to identify and rank critical factors influencing collaboration between startups and large organisations, leading to enhanced innovation performance [51]. Additionally, MCDM has facilitated knowledge management and collaboration by fostering environments that support innovation [52]. Hybrid MCDM approaches, which combine several MCDM techniques, further enhance decision-making by integrating diverse criteria and perspectives, ensuring greater robustness and adaptability [49, 53].

Some MCDM methodologies offer robust frameworks for decision-making. For instance, the Analytic Hierarchy Process (AHP) organizes decision problems hierarchically, aligning goals, criteria, and sub-criteria to address complex decisions effectively [53]. Similarly, methods like the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) compare alternatives to ideal solutions, helping evaluate and select optimal options [54].

In the context of this study, it focuses on addressing vulnerabilities and building resilience in the Caribbean. The structured approach of ISM provides contextually relevant insights for decision-making, leading to sustainable outcomes in regions with complex challenges [50]. Specifically, ISM has proven highly effective for complex research questions, as it differentiates between driving and dependent factors and maps their interrelationships [55, 56]. Its ability to identify, quantify, and prioritize factors by analyzing hierarchical and causal structures makes it especially suitable for exploring the intricate dynamics of OI and resilience-building [57, 58]. Moreover, ISM has demonstrated its versatility in various research domains, including innovation studies. For example, it has been used to identify and analyse the relationships among key factors such as diversity, empowerment, and training as drivers of organisational innovation [59].

While other methodologies, such as AHP and fuzzy MCDM, are adept at handling ambiguity and prioritization, ISM excels in elucidating complex interdependencies and guiding actionable steps. This capability aligns closely with the study's objectives, particularly in addressing the vulnerabilities and data limitations specific to the Caribbean [60].

4.2 Research Design

This study utilizes the ISM method to analyse complex relationships and enhance the understanding of MCDM tools and techniques. Figure 1 presents the proposed research methodology flowchart.

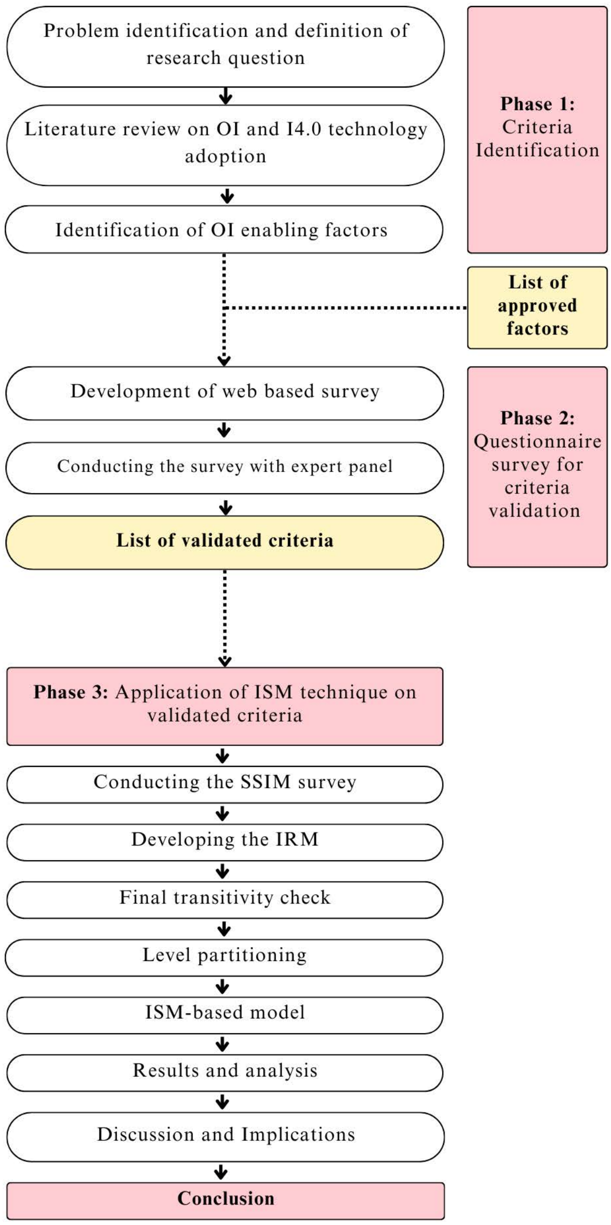

Figure 1. The framework of analysing OI enabling factors influencing I4.0 technology adoption in small manufacturing firms

4.3 Data Collection

Non-probability sampling involves selecting sample units without predetermined inclusion probabilities, distinguishing it from probability sampling, which relies on randomization. This study adopted purposive sampling, a subtype of non-probability sampling, due to its effectiveness in targeting niche populations with specialized expertise [61, 62]. Purposive sampling is widely acknowledged for its suitability in identifying knowledgeable informants in both qualitative and quantitative research [63]. It is particularly valuable in ISM studies, where domain-specific expertise is essential.

The purposive sampling approach involves selecting individuals with substantial expertise and experience in the relevant research domain [61]. Applications of this method include Sirimewan et al. [64], who applied ISM and Socio-Technical Systems (STSs) theory to sustainable decision-making with sixteen participants, and Zaman et al. [65], who utilized a hybrid ISM-DEMATEL approach to identify critical factors for digital banking resilience, relying on five expert participants.

In this study, academic researchers and senior managers from small manufacturing firms in the Caribbean non-energy sector were selected based on their specialized knowledge and extensive experience in technological innovation. Experts were contacted to obtain their formal consent to participate. Upon agreement, detailed questionnaires were sent electronically, accompanied by clear instructions. Where necessary, verbal explanations were provided to ensure clarity and accuracy during data collection.

Seven experts, with considerable experience in research and senior managerial decision-making roles related to technology adoption, participated in this study. Their roles included Professor, General Manager: Manufacturing Industry, Senior Lecturer, Change Management Consultant, Technology Implementation Specialist, Supply Chain and Logistics Manager: Manufacturing Industry, and Research Fellow, as summarized in Table 2. These experts had an average of 13 years of professional experience and demonstrated specialized knowledge in manufacturing operations, cloud computing adoption, risk assessment, and technology-driven innovation.

Table 2. Professional profile of study participants

Participant	Professional Title	Years of Experience
Participant 1	Change Management Consultant	13
Participant 2	Technology Implementation Specialist	9
Participant 3	General Manager: Manufacturing Industry	20
Participant 4	Supply Chain and Logistics Manager: Manufacturing Industry	7
Participant 5	Research Fellow	8
Participant 6	Senior Lecturer	17
Participant 7	Professor	25

5 Research Methods

5.1 Overview of the ISM Methodology

The ISM methodology is implemented to identify and analyse relationships among specific variables that define a complex problem or issue [66]. ISM combines scientific and lay perspectives to create graphical representations of system composition and structure, facilitating communication between technical experts and the public [67]. ISM is therefore intended for use when systematic and logical thinking is required to approach a complex issue under consideration [67, 68]. Based on the literature reviewed for ISM applications, the procedure of the ISM approach is depicted in six steps (see Table 3).

5.2 ISM Method Application

5.2.1 Structural self-interaction matrix (SSIM) development

The SSIM is created to represent the pairwise relationships between factors "i" and "j" displayed along the vertical and horizontal axes, respectively. This matrix is developed based on expert analysis and is presented in Table 4.

Experts assign one of four symbols to each relationship to indicate the direction of influence between the two elements. These symbols are selected in accordance with Step 2 and are defined as follows:

V — if factor "i" will support/help factor "j";

A — if factor "j" will support/help factor "i";

X — if factor "j" and "i" will support/help each other;
O — if factor "j" and factor "i" are not related.

Table 3. A 6-step ISM approach

Steps	Descriptions
1: Factor Identification	The relevant factors or variables are identified that are significant to the problem being studied. These factors are carefully selected based on their relevance to the research objectives.
2: Creation of the Structural Self-Interaction Matrix (SSIM)	The SSIM is developed through expert analysis, where relationships between the identified factors are established. These relationships are defined according to the research objectives, providing a foundation for further analysis.
3: Conversion to Initial Reachability Matrix (IRM)	The SSIM is converted into a binary format, resulting in the Initial Reachability Matrix (IRM). This matrix represents the presence or absence of direct relationships between the factors.
4: Formation of the Final Reachability Matrix (FRM)	The IRM undergoes a transitivity check, ensuring that indirect relationships are accounted for. This leads to the creation of the Final Reachability Matrix (FRM), which captures both direct and indirect relationships between factors.
5: Partitioning of Factors	The factors are partitioned into different levels based on the FRM. This step organizes the factors hierarchically, identifying which factors influence others and which are influenced.
6: Creation of the ISM Hierarchical Structure	The ISM hierarchical structure is constructed in the form of a digraph, where the factors are represented as nodes. The relationships between the factors are visualized using arrows to show the direction of influence.

Table 4. SSIM

i/j	Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1	Dynamic Managerial Capabilities		V	V	V	V	V	O	O	V	V	V	V	O
F2	Business Model Openness			A	A	A	V	A	A	V	V	V	V	V
F3	Government Support Mechanisms				X	X	V	O	O	V	X	X	V	X
F4	Ecosystems for Technology Transfer					A	V	O	O	V	X	O	V	V
F5	Collaborative Networks						V	O	O	V	X	O	V	V
F6	R&D Investment Capability							O	O	V	V	V	V	A
F7	Competitive Pressure								O	V	O	V	V	O
F8	Customer Pressure									V	O	V	V	O
F9	Digital Transformation										X	V	V	A
F10	Digital Trust											V	V	A
F11	Internal Knowledge Flows												V	O
F12	Adaption to Global Best Practices													A
F13	External Knowledge Flows													

5.2.2 IRM

The IRM, as illustrated in Table 5, is derived by converting the symbolic codes (V, A, X, and O) from the SSIM into binary digits ('0' and '1'). The conversion follows these specific rules:

– If the relationship is denoted as "V" on the (i, j) axis, its binary equivalent is '1', while on the (j, i) axis, it is '0'.

– If the relationship is “*A*” on the (*i*, *j*) axis, its binary equivalent is ‘0’, while on the (*j*, *i*) axis, it is ‘1’.
– If the relationship is “*X*” on the (*i*, j) axis, its binary equivalent is ‘1’, and on the (*j*, *i*) axis, it is also ‘1’.
– If the relationship is “*O*” on both the (*i*, *j*) and (*j*, *i*) axes, its binary equivalent is ‘0’.

Table 5. IRM

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	Driving Power
Dynamic Managerial Capabilities	1	1	1	1	1	1	0	0	1	1	1	1	0	**10**
Business Model Openness	0	1	0	0	0	1	0	0	1	1	1	1	1	**7**
Government Support Mechanisms	0	1	1	1	1	1	0	0	1	1	1	1	1	**10**
Ecosystems for Technology Transfer	0	1	1	1	0	1	0	0	1	1	0	1	1	**8**
Collaborative Networks	0	1	1	1	1	1	0	0	1	1	0	1	1	**9**
R&D Investment Capability	0	0	0	0	0	1	0	0	1	1	1	1	0	**5**
Competitive Pressure	0	1	0	0	0	0	1	0	1	0	1	1	0	**5**
Customer Pressure	0	1	0	0	0	0	0	1	1	0	1	1	0	**5**
Digital Transformation	0	0	0	0	0	0	0	0	1	1	1	1	0	**4**
Digital Trust	0	0	1	1	1	0	0	0	1	1	1	1	0	**7**
Internal Knowledge Flows	0	0	1	0	0	0	0	0	0	0	1	1	0	**3**
Adaption to Global Best Practices	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
External Knowledge Flows	0	0	1	0	0	1	0	0	1	1	0	1	1	**6**
Dependence Power	**1**	**7**	**7**	**5**	**4**	**7**	**1**	**1**	**11**	**9**	**9**	**13**	**5**	

5.2.3 FRM

The FRM, as illustrated in Table 6, is developed by applying the principle of transitivity. According to this rule, if “Factor A” is related to “Factor B” and “Factor B” is related to “Factor C,” then “Factor A” is inherently related to “Factor C.” By systematically applying this rule, the FRM is constructed.

Table 6. FRM

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	Driving Power
Dynamic Managerial Capabilities	1	1	1	1	1	1	0	0	1	1	1	1	1*	**11**
Business Model Openness	0	1	1*	1*	1*	1	0	0	1	1	1	1	1	**10**
Government Support Mechanisms	0	1	1	1	1	1	0	0	1	1	1	1	1	**10**
Ecosystems for Technology Transfer	0	1	1	1	1*	1	0	0	1	1	1*	1	1	**10**
Collaborative Networks	0	1	1	1	1	1	0	0	1	1	1*	1	1	**10**
R&D Investment Capability	0	1*	1*	1*	1*	1	0	0	1	1	1	1	1*	**10**
Competitive Pressure	0	1	1*	1*	1*	1*	1	0	1	1*	1	1	1*	**11**
Customer Pressure	0	1	1*	1*	1*	1*	0	1	1	1*	1	1	1*	**11**
Digital Transformation	0	1*	1*	1*	1*	1*	0	0	1	1	1	1	1*	**10**
Digital Trust	0	1*	1	1	1	1*	0	0	1	1	1	1	1*	**10**
Internal Knowledge Flows	0	1*	1	1*	1*	1*	0	0	1*	1*	1	1	1*	**10**
Adaption to Global Best Practices	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
External Knowledge Flows	0	1*	1	1*	1*	1	0	0	1	1	1*	1	1	**10**
Dependence Power	**1**	**12**	**12**	**12**	**12**	**12**	**1**	**1**	**12**	**12**	**12**	**13**	**12**	

Notes: * indicates a direct relationship or connection between two factors

In the matrix, the driving power of a factor is calculated as the total number of elements present in its row, representing the extent to which the factor influences others. Conversely, the dependence power of a factor is determined by the total number of elements in its column, indicating the degree to which the factor is influenced by others.

5.2.4 Level Partitioning (LP)

From the FRM, the reachability set, and antecedent set are derived for each factor. The reachability set includes the factor itself and all other factors it influences, while the antecedent set comprises the factor itself and all factors that influence it. The intersection of these sets is then calculated for each factor to determine their levels within the ISM hierarchy.

Factors for which the reachability set, and intersection set are identical are assigned to the top level of the hierarchy. These top-level factors do not influence any factors above their own level. Once identified, these factors are removed from further consideration. The process is repeated to identify factors at subsequent levels. This iterative approach continues until all factors are assigned a level, providing a clear structure for building the digraph and the final ISM model. Table 7 shows the final factor interactions levels, where the factors are categorized into different levels based on their influence or dependency on other elements, creating a clear hierarchical structure.

Table 7. Final factor interaction levels

Factor Code	Reachability Set	Antecedent Set	Intersection Set	Level
F12	12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13,	12,	1
F2	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F3	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F4	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F5	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F6	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F9	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F10	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F11	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F13	2, 3, 4, 5, 6, 9, 10, 11, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13,	2, 3, 4, 5, 6, 9, 10, 11, 13,	2
F1	1,	1,	1,	3
F7	7,	7,	7,	3
F8	8,	8,	8,	3

5.3 Building the ISM-Model

The ISM-based hierarchical model is developed (as shown in Figure 2) following the LP of factors. This model organizes attributes across three distinct levels.

In this study, Level I comprises "Adaptation to Global Best Practices (F12)," which exhibits the highest dependence power. This indicates that F12 relies on all other factors located at the other levels. This is the outcome, or dependent factor, with no further influence on other factors. At the opposite end of the hierarchy, Level III includes the most critical factors: "Dynamic Managerial Capabilities (F1)," "Competitive Pressure (F7)," and "Customer Pressure (F8)." These factors act as primary drivers, influencing all other factors positioned higher in the hierarchy. These factors are independent factors, as they only reach themselves.

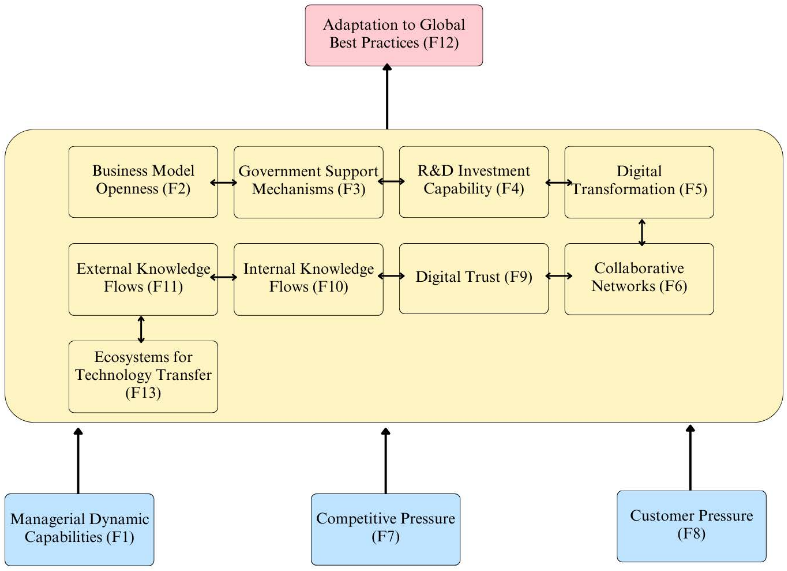

Figure 2. ISM-based hierarchical digraph

Level II comprises a range of factors that are both influenced by Level III factors and, in turn, affect Level I. These include “Business Model Openness (F2),” “Government Support Mechanisms (F3),” “Ecosystems for Technology Transfer (F4),” “Collaborative Networks (F5),” “R&D Investment Capability (F6),” “Digital Transformation (F9),” “Digital Trust (F10),” “Internal Knowledge Flows (F11),” and “External Knowledge Flows (F13).” These factors share similar relationships, where they both influence and are influenced by other factors.

The hierarchical structure reflects the interdependencies among these factors, providing a clear visualization of how lower-level factors drive the dynamics of upper-level factors within the ISM framework.

6 Discussion

The economies of the Global South, particularly the Caribbean SIDS, are under-researched in the context of OI and technology adoption. Most studies on OI and I4.0 in this region employ qualitative methodologies, as evidenced by Bhola-Paul [12]. This study aimed to explain the interrelationships among OI-enabling factors and their influence on I4.0 adoption by small manufacturing firms in the non-energy sector of Caribbean SIDS. By employing the MCDM approach, which utilized ISM, the study developed and validated a robust framework that links critical factors influencing OI and I4.0 adoption.

The results identify “Dynamic Managerial Capabilities (F1),” “Competitive Pressure (F7),” and “Customer Pressure (F8)” as foundational factors that drive the OI ecosystem and significantly influence the adoption of I4.0 technologies. Their presence or absence directly affects outcomes such as “Adaptation to Global Best Practices (F12)”. This implies that managers must possess the ability to dynamically adapt strategies, processes, and organisational structures to align with evolving market conditions and innovation needs. The findings further infer that strong managerial capabilities underpin decision-making and execution in response to pressures. Studies by Ferreir and Coelho [69] and Helfat and Martin [70] underscore the importance of managerial dynamic capabilities as push factors—encompassing managerial cognition, social capital, and human capital—in enabling firms to sense opportunities, transform resources, and respond to external pressures such as competition and customer demands.

Additionally, the results identify that firms are compelled to OI and adopt best practices due to competition and customer demands. This infers that competitive pressure pulls organisations to explore new technologies, improve efficiency, and maintain relevance in the market. The literature supports that competition can drive OI by encouraging firms to create new products and services, improve production processes, and collaborate with suppliers [71]. Moreover, the findings imply that customer expectations for quality, affordability, and innovation pull firms to improve products, processes, and services, ensuring that OI practices remain relevant and customer-centric. This is supported by literature that found that small firms often innovate to meet customer demands and react to market opportunities [72].

The study found that anticipating competitive and customer pressures driven by managerial capabilities helps firms achieve critical intermediary factors such as "Business Model Openness (F2)," "Government Support Mechanisms (F3)," "Ecosystems for Technology Transfer (F4)," and "Collaborative Networks (F5)." These factors not only act as enablers but also influence one another, creating a networked infrastructure that fosters OI and I4.0 adoption. Hence, intermediary factors are closer to the operational level and represent more actionable elements (e.g., R&D Investment Capability or Digital Transformation). This implies that driving factors influence intermediary factors (e.g., (F3), (F4) and (F5)) that, in turn, enable the system's outcomes, such as global best practice adaptation. This is supported by the findings of Chan et al. [73] and Torres de Oliveira et al. [74], which highlight how the strategic use of IT, inter-organisational relationships, and absorptive capacity enable small firms to overcome barriers and leverage knowledge flows effectively.

Specific factors, for example, "Ecosystems for Technology Transfer (F4)" and "Collaborative Networks (F5)" are interdependent. The findings are supported by Broome et al. [75], who suggest that firms with strong technological orientations are more likely to adopt digital tools, which in turn facilitates innovation through R&D investments. Similarly, "Government Support Mechanisms (F3)" play a crucial role in mitigating market failures, the effects of which are emphasized by recent research from Acevedo et al. [7], including insufficient awareness of innovation benefits and limited human capital.

The findings position "Adaptation to Global Best Practices (F12)" as the ultimate dependent factor, shaped by the interplay of foundational and intermediary factors. Its successful implementation depends on enablers such as "Dynamic Managerial Capabilities (F1)" and external pressures (F7, F8), which create the conditions necessary for firms to align with global standards. Bolatan et al. [76] and Ghobakhloo and Ching [77] support this view, showing how managerial support, financial resources, and social capital facilitate the adoption of global best practices. As the dependent factor, "Adaptation to Global Best Practices (F12)" reflects the goal or benchmark that firms aim to achieve in their OI practices. This objective can be a differentiator of success for small manufacturers in their I4.0 pursuits, as authors including Sá et al. [16] found that global best practices in OI strategies enhance innovation performance, promote globalization, and facilitate collaboration across industries and countries [78–80].

6.1 Practical and Managerial Implications

Utilizing an ISM-based hierarchical model, the study establishes a structured framework that elucidates the critical factors propelling OI and I4.0 adoption. Considering these findings, several practical and managerial implications are explored for enhancing the adoption of I4.0 technologies in the non-energy manufacturing sector of Caribbean SIDS. These are:

1) **Managerial Dynamic Capabilities, Competitive Pressure, and Customer Pressure as Key Drivers**: In Caribbean SIDS, the critical drivers of OI for I4.0 technology adoption are "Managerial Dynamic Capabilities (F1)," "Competitive Pressure (F7)," and "Customer Pressure (F8)." These factors represent pivotal intervention points for organisations and policymakers seeking to enhance regional technological capabilities. In the unique context of Caribbean SIDS, where firms often operate in small markets with limited resources, improving managerial capabilities is essential. Equipping leaders with dynamic skills enables them to effectively navigate customer-driven demands and competitive pressures, fostering a more adaptable and innovative ecosystem. Additionally, proactive mechanisms to monitor market trends and customer expectations can enable firms to anticipate shifts and respond strategically. Policies and investments that prioritize management development and provide financial and technical support to firms can amplify these efforts, creating ripple effects that benefit the entire non-energy manufacturing sector.

2) **Leveraging OI for Affordable and Scalable Solutions**: The results infer that for small manufacturers, technology adoption frequently results from external pressures, such as customer demands and competitive forces, rather than from proactive innovation strategies. Given the resource constraints faced by many regional firms, leveraging OI practices—such as partnerships, collaborations, and external knowledge acquisition—offers a viable pathway for accessing affordable and scalable I4.0 solutions. OI allows firms to tap into external expertise and technologies, reducing the financial and infrastructural burden associated with I4.0 adoption. By integrating OI practices, Caribbean manufacturers can better align with customer needs, maintain competitiveness in global supply chains, and accelerate their adoption of advanced technologies. This approach is particularly significant for SMEs in the region, who often struggle to sustain standalone innovation initiatives.

3) **Moving Beyond Reactive Innovation and Adapting to Global Standards**: The adaptation of global best practices in Caribbean SIDS often occurs reactively, pulled by customer and competitive pressures rather than

strategic foresight. Firms in the region frequently adopt international standards to remain relevant in the global supply chain, but this reliance on external triggers can limit their ability to develop a unique value proposition or competitive edge. The challenge is exacerbated for smaller firms, which often lack the financial and human capital needed to innovate proactively or invest in advanced technologies. This reactive approach leads to short-term fixes that may fail to establish long-term innovation capabilities. To address this, strengthening managerial capabilities through training in strategic planning and environmental scanning is critical. Policymakers should encourage proactive innovation by offering grants, subsidies, and collaborative platforms that reduce the barriers to innovation. Furthermore, fostering partnerships with larger firms, research institutions, and governments can provide access to global resources and expertise. Building technology readiness, including robust IT infrastructure and a skilled workforce, will ensure that firms in the region can transition from reactive to proactive innovation strategies.

4) **Driving Adaptation to Global Best Practices for I4.0 Adoption in Non-Competitive Environments**: In non-competitive environments, the dependence of adaptation to global practices on other factors in the ISM, and its connection to I4.0 adoption, suggests that external pressures such as customer expectations, regulatory requirements, and global market trends can drive firms toward global alignment and technology adoption. In the absence of competition, organisations must adopt proactive strategies, leveraging managerial dynamic capabilities and OI practices to achieve long-term relevance and operational efficiency. Intrinsic motivations, such as enhancing resilience, improving productivity, and meeting sustainability goals, also emerge as critical triggers for adaptation and I4.0 adoption. Furthermore, integrating with global practices ensures firms maintain their relevance in international markets and supply chains, opening opportunities for exports and partnerships. To support this, government policies, incentives, and collaborative initiatives become crucial, providing resources for technological readiness, workforce development, and international collaboration. While competition often acts as a catalyst, this highlights that adaptation to global practices and I4.0 adoption can flourish in non-competitive settings with robust strategic, managerial, and policy-driven frameworks.

The empirical insights are consolidated and demonstrated through a networked ecosystem framework, illustrated in Figure 3, which highlights the enablers of OI that drive the adoption of I4.0 technologies among Caribbean small firms.

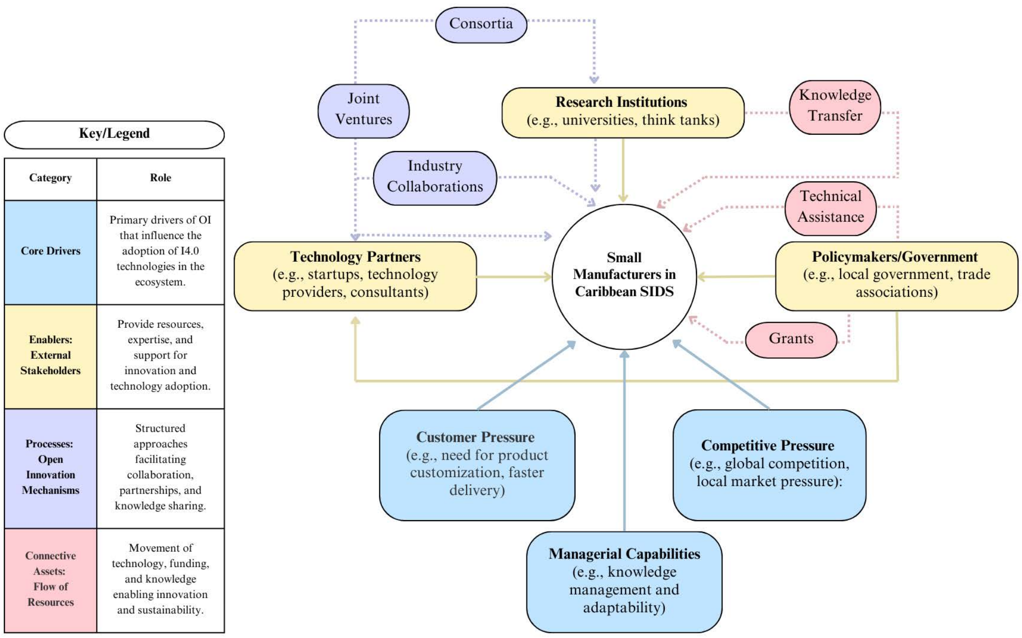

Figure 3. Networked ecosystem framework highlighting OI enablers for I4.0 adoption in Caribbean small firms

7 Conclusions

Across the globe, specifically in developing countries, small organisations are considered pivotal to economic expansion. In the Caribbean economy, small firms play a central role in job creation, innovation, and economic development, representing 95% of businesses and contributing 40% to the region's GDP. Despite their importance, SMEs in the Caribbean rank lowest in organisational innovation, at only 4% [12]. Additionally, SMEs contribute between 40% and 70% of the region's GDP [4].

To compete in global markets, SMEs in developing countries often rely heavily on partnerships for economic and business advancements and successful technology adoption [56]. Some researchers have observed the importance of I4.0 technologies in innovation pursuits using qualitative methods. However, studies in the context of decision-making frameworks are limited, and understanding of the enabling OI factors that promote technology adoption is unclear.

This study was sought to analyse the OI-enabling factors that support the adoption of I4.0 technologies in small manufacturing firms in the non-energy sector. Thirteen critical OI-enabling factors after the validation of experts have been identified. For further ranking and to test interrelationships between these enablers, the ISM approach is used. The hierarchical structure shows how factors influence one another, helping prioritize areas for action or focus.

OI in small manufacturers in Caribbean SIDS appears driven by external pull factors, primarily customer and competitive demands, interpreted through managerial scanning capabilities. This reactive approach underscores the need for strategic interventions to enable more proactive, resource-efficient, and sustainable innovation practices.

Nevertheless, the presence of intermediary factors highlights that the path to OI success for small manufacturers in Caribbean SIDS is multifaceted and requires addressing foundational enablers. They make it possible to translate strategic intentions into specific initiatives, such as fostering collaboration, building trust in digital systems, or leveraging internal and external knowledge flows. Competitive and customer pressures act as starting points, but achieving sustained innovation depends on strategically navigating through these intermediary capabilities. This framework emphasizes the importance of creating a holistic environment where external pressures drive internal transformation and long-term competitiveness.

7.1 Limitations and Future Research

The study revealed a dynamic interplay of motivations and strategic considerations that shape the OI practices of small manufacturers adopting I4.0 technologies. The ISM results confirmed the reliability of the enabling factors across varying literature, suggesting a generalizable model. These findings highlight the importance of understanding the foundational and intermediary factors within an OI ecosystem. However, several limitations should be considered.

First, the research is confined to non-energy manufacturing firms in Caribbean SIDS, providing a focused analysis of the region's unique challenges, but restricting the generalizability of findings to other industries or geographic regions.

Second, the study tests only thirteen factors, which, while insightful, may limit the comprehensiveness of the framework. Including additional factors could enhance the model's robustness and applicability.

Third, the use of ISM methodology introduces potential biases. ISM relies heavily on subjective expert judgment to identify and structure critical factors, which may affect the accuracy of factor prioritization, and the relationships established between them. Additionally, the absence of extensive empirical validation reduces the model's reliability and applicability across diverse contexts.

To address these limitations, future studies should consider the following:

1) Incorporating Structural Equation Modelling (SEM): SEM could be employed to validate the ISM model's reliability and predictive power. By leveraging larger sample sizes, especially from small firms, SEM can provide a more robust statistical basis for the identified relationships.

2) Expanding the Scope of Application: The identified factors should be tested in other sectors and industries or in developing economies beyond Caribbean SIDS. Such studies would enable comparisons across regions and sectors, offering a broader understanding of I4.0 adoption dynamics.

3) Considering Temporal Dynamics: This study does not explore how OI-enabling factors influencing I4.0 adoption evolve over time, limiting its ability to assess the long-term effectiveness of derived strategies. For instance, factors such as competitive pressure may diminish in influence as firms adapt to industry norms. Longitudinal studies tracking these dynamics would provide valuable insights into the sustained impact of these factors.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflict of Interests

The authors declare no conflict of interest.

References

[1] Y. Lu, "Industry 4.0: A survey on technologies, applications and open research issues," *J. Ind. Inf. Integr.*, vol. 6, pp. 1–10, 2017. https://doi.org/10.1016/J.JII.2017.04.005

[2] R. Kumar, R. K. Singh, and Y. K. Dwivedi, "Application of Industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges," *J. Clean. Prod.*, vol. 275, p. 124063, 2020. https://doi.org/10.1016/j.jclepro.2020.124063

[3] A. Raj, G. Dwivedi, A. Sharma, A. B. L. De Sousa Jabbour, and S. Rajak, "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective," *Int. J. Prod. Econ.*, vol. 224, p. 107546, 2020. https://doi.org/10.1016/j.ijpe.2019.107546

[4] P. Coke-Hamilton, *The Role of SMEs in the Caribbean*. Hamburg: EU-LAC Foundation, 2013.

[5] P. Mohan and E. Strobl, "COVID-19, firm innovation strategy, and production efficiency: A stochastic frontier analysis of Caribbean firms," *Inter-Am. Invest. Corp. (IIC)*, 2023. https://doi.org/10.18235/0004775

[6] P. Mohan, E. Strobl, and P. Watson, "Barriers to innovation and firm productivity in the Caribbean," in *Exploring Firm-Level Innovation and Productivity in Developing Countries: The Perspective of Caribbean Small States*. Washington, DC: Inter-American Development Bank, 2017.

[7] M. C. Acevedo, R. Garcia, J. Lennon, and S. Pereira, "Innovation and firm performance in the Caribbean," *Inter-Am. Invest. Corp. (IIC)*, 2023. https://idbinvest.org/en/publications/innovation-and-firm-performance-caribbean

[8] J. Khadan, "How much do workforce skills matter for innovation in the Caribbean?" 2018. https://blogs.iadb.org/caribbean-dev-trends/en/8925/

[9] H. W. Chesbrough, "The era of open innovation," *MIT Sloan Manag. Rev.*, vol. 44, no. 3, pp. 35–41, 2003.

[10] M. Bogers, H. Chesbrough, and C. Moedas, "Open innovation: Research, practices, and policies," *Calif. Manag. Rev.*, vol. 60, no. 2, pp. 5–16, 2018. https://doi.org/10.1177/0008125617745086

[11] "SIDS 2.0: Defining the pathway for small islands digital states in the caribbean," in *High Level Conference: SIDS 2.0: Defining the Pathway for Small Islands DIGITAL States in the Caribbean*. Ministry of Digital Transformation, Government of Trinidad and Tobago, UNDP, CAF, & IDB, 2024. https://www.undp.org/sites/g/files/zskgke326/files/2024-06/sids-2.0-initiative-digital-pathways-for-the-caribbean-final-outcome-statement-v02.pdf

[12] H. M. Bhola-Paul, "Leadership experiences of organization open innovation in Caribbean small and medium enterprises," Doctoral thesis, Walden University, US, 2022.

[13] V. Gupta, L. Rubalcaba, J. M. Fernandez-Crehuet, and L. F. Pereira, "Innovation through startup collaboration: Build a relationship with your peer startups," *IEEE Eng. Manag. Rev.*, vol. 49, no. 3, pp. 126–135, 2021. https://doi.org/10.1109/emr.2021.3101116

[14] J. Woods, B. Galbraith, and N. Hewitt-Dundas, "Network centrality and open innovation: A social network analysis of an SME manufacturing cluster," *IEEE Trans. Eng. Manag.*, vol. 69, no. 2, pp. 351–364, 2019. https://doi.org/10.1109/TEM.2019.2934765

[15] M. M. Gobble, "Defining open innovation," *Res. Technol. Manag.*, vol. 59, no. 5, pp. 63–67, 2016. https://doi.org/10.1080/08956308.2016.1209029

[16] T. Sá, J. J. Ferreira, and S. Jayantilal, "Open innovation strategy: A systematic literature review," *Eur. J. Innov. Manag.*, 2023. https://doi.org/10.1108/ejim-11-2022-0638

[17] L. Dahlander and D. M. Gann, "How open is innovation?" *Res. Policy*, vol. 39, no. 6, pp. 699–709, 2010. https://doi.org/10.1016/J.RESPOL.2010.01.013

[18] A. P. V. B. V. Lopes and M. M. de Carvalho, "Evolution of the open innovation paradigm: Towards a contingent conceptual model," *Technol. Forecast. Soc. Change*, vol. 132, pp. 284–298, 2018. https://doi.org/10.1016/J.TECHFORE.2018.02.014

[19] I. M. Ar, "The concept of open innovation," in *Open Innovation and Knowledge Management in Small and Medium Enterprises*. Singapore: World Scientific Publishing, 2018, pp. 35–52. https://doi.org/10.1142/9789813233591_0003

[20] L. Pujol Priego, D. Osimo, and J. D. Wareham, "Data sharing practice in big data ecosystems," 2019, ESADE Business School Research Paper No. 273. https://doi.org/10.2139/ssrn.3355696

[21] H. Munir, K. Wnuk, and P. Runeson, "Open innovation in software engineering: A systematic mapping study," *Empir. Software Eng.*, vol. 21, pp. 684–723, 2016. https://doi.org/10.1007/s10664-015-9380-x

[22] D. Aloini, V. Lazzarotti, R. Manzini, and L. Pellegrini, "Implementing open innovation: Technological, organizational and managerial tools," *Bus. Process. Manag. J.*, vol. 23, no. 6, pp. 1086–1093, 2017. https://doi.org/10.1108/BPMJ-10-2016-0203

[23] P. T. Gianiodis, S. C. Ellis, and E. Secchi, "Advancing a typology of open innovation," *Int. J. Innov. Manag.*, vol. 14, no. 4, pp. 531–572, 2010. https://doi.org/10.1142/S1363919610002775

[24] H. Chesbrough, "Managing open innovation," *Res. Technol. Manag.*, vol. 47, no. 1, pp. 23–26, 2004. https://doi.org/10.1080/08956308.2004.11671604

[25] M. Prváková, "Factors of open innovation," *Stud. Commer. Bratisl.*, vol. 13, no. 2, pp. 160–173, 2020. https://doi.org/10.2478/stcb-2020-0007

[26] R. Dagher, "Policy space under a constraining combination–Open economies, austerity and small island states," *Third World Q.*, vol. 40, no. 6, pp. 1040–1063, 2019. https://doi.org/10.1080/01436597.2019.1574563

[27] E. Hopali and Ö. Vayvay, "Industry 4.0 as the last industrial revolution and its opportunities for developing countries," in *Analyzing the Impacts of Industry 4.0 in Modern Business Environments*. PA: IGI Global, 2018, pp. 65–80. https://doi.org/10.4018/978-1-5225-3468-6.ch004

[28] L. O. Cezarino, L. B. Liboni, N. O. Stefanelli, B. G. Oliveira, and L. C. Stocco, "Diving into emerging economies bottleneck: Industry 4.0 and implications for circular economy," *Manag. Decis.*, vol. 59, no. 8, pp. 1841–1862, 2021. https://doi.org/10.1108/MD-10-2018-1084

[29] *Industry 4.0 for Inclusive Development*. Switzerland: United Nations Conference on Trade and Development, 2022. https://doi.org/10.18356/9789210014441

[30] I. S. Khan, M. O. Ahmad, and J. Majava, "Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives," *J. Clean. Prod.*, vol. 297, p. 126655, 2021. https://doi.org/10.1016/J.JCLEPRO.2021.126655

[31] H. Yüksel, "An empirical evaluation of industry 4.0 applications of companies in Turkey: The case of a developing country," *Technol. Soc.*, vol. 63, p. 101364, 2020. https://doi.org/10.1016/j.techsoc.2020.101364

[32] J. H. Roodt and H. Koen, "A review of hurdles to adopting Industry 4.0 in developing countries," *INCOSE Int. Symp.*, vol. 30, no. 1, pp. 1079–1092, 2020. https://doi.org/10.1002/j.2334-5837.2020.00773.x

[33] R. Bruni and M. Piccarozzi, "Industry 4.0 enablers in retailing: A literature review," *Int. J. Retail Distrib. Manag.*, vol. 50, no. 7, pp. 816–838, 2022. https://doi.org/10.1108/IJRDM-07-2021-0314

[34] S. Khin and D. M. H. Kee, "Factors influencing Industry 4.0 adoption," *J. Manuf. Technol. Manag.*, vol. 33, no. 3, pp. 448–467, 2022. https://doi.org/10.1108/jmtm-03-2021-0111

[35] Caribbean Development Bank, "Micro, small & medium enterprise development in the Caribbean: Towards a new frontier," 2016. https://www.caribank.org/publications-and-resources/resource-library/thematic-papers/micro-small-and-medium-enterprise-development-caribbean-towards-new-frontier

[36] A. V. Bogoviz, V. S. Osipov, M. K. Chistyakova, and M. Y. Borisov, "Comparative analysis of formation of Industry 4.0 in developed and developing countries," in *Industry 4.0: Industrial Revolution of the 21st Century*. Springer, 2019, pp. 155–164. https://doi.org/10.1007/978-3-319-94310-7_15

[37] Y. X. Liao, E. R. Loures, F. Deschamps, G. Brezinski, and A. Venâncio, "The impact of the fourth industrial revolution: A cross-country/region comparison," *Prod.*, vol. 28, p. e20180061, 2018. https://doi.org/10.1590/0103-6513.20180061

[38] G. Crespi, S. Dohnert, A. Maffioli, A. M. Hoelz Pinto Ambrozio, M. Barron, F. Bernini, L. Figal Garone, K. Grant, P. Mohan, D. Morris, A. Presbitero, R. Rabellotti, F. Lage de Sousa, E. Strobl, and P. Watson, *Exploring Firm-Level Innovation and Productivity in Developing Countries: The Perspective of Caribbean Small States*. New York: Inter-American Development Bank, 2017. https://doi.org/10.18235/0000616

[39] H. W. Chesbrough, "How smaller companies can benefit from open innovation," *Econ. Cult. Hist. Jpn. Spotlight*, pp. 13–15, 2010. https://www.jef.or.jp/journal/pdf/169th_cover03.pdf

[40] D. Q. Nguyen, "How firms accumulate knowledge to innovate – An empirical study of Vietnamese firms," *Manag. Decis.*, vol. 60, no. 5, pp. 1413–1437, 2022. https://doi.org/10.1108/MD-11-2020-1546

[41] M. Anshari and M. N. Almunawar, "Adopting open innovation for SMEs and industrial revolution 4.0," *J. Sci. Technol. Policy Manag.*, vol. 13, no. 2, pp. 405–427, 2022. https://doi.org/10.1108/JSTPM-03-2020-0061

[42] H. Chesbrough, *Open Services Innovation: Rethinking Your Business to Grow and Compete in a New Era*. San Francisco: Jossey-Bass, 2011.

[43] S. S. Alam, S. Susmit, C. Y. Lin, M. Masukujjaman, and Y. H. Ho, "Factors affecting augmented reality adoption in the retail industry," *J. Open Innov.: Technol. Mark. Complex.*, vol. 7, no. 2, p. 142, 2021.

https://doi.org/10.3390/joitmc7020142
[44] C. S. R. Nuthalapati and C. Nuthalapati, “Has open innovation taken root in India? Evidence from startups working in food value chains,” *Circ. Econ. Sustain.*, vol. 1, no. 4, pp. 1207–1230, 2021. https://doi.org/10.1007/s43615-021-00074-5
[45] M. L. A. Díaz, F. A. R. Ordoñez, and R. A. T. Muñoz, “Open innovation and public policies in developing countries,” *Int. J. Qual. Res.*, vol. 14, no. 3, pp. 787–804, 2020. https://doi.org/10.24874/IJQR14.03-09
[46] A. Koh, E. Kong, and G. Timperio, “An analysis of open innovation determinants: The case study of Singapore based family-owned enterprises,” *Eur. J. Fam. Bus.*, vol. 9, no. 2, pp. 85–101, 2019. https://doi.org/10.24310/ejfbejfb.v9i2.5678
[47] G. D. Sharma, S. Kraus, M. Srivastava, R. Chopra, and A. Kallmuenzer, “The changing role of innovation for crisis management in times of COVID-19: An integrative literature review,” *J. Innov. Knowl.*, vol. 7, no. 4, p. 100281, 2022. https://doi.org/10.1016/j.jik.2022.100281
[48] R. Alkhazaleh, K. Mykoniatis, and A. Alahmer, “The success of technology transfer in the Industry 4.0 era: A systematic literature review,” *J. Open Innov. Technol. Mark. Complex.*, vol. 8, no. 4, p. 202, 2022. https://doi.org/10.3390/joitmc8040202
[49] P. A. Alvarez, A. Ishizaka, and L. Martínez, “Multiple-criteria decision-making sorting methods: A survey,” *Expert Syst. Appl.*, vol. 183, p. 115368, 2021. https://doi.org/10.1016/j.eswa.2021.115368
[50] M. Schwaninger, “Integrative systems methodology: Heuristic for requisite variety,” *Int. Trans. Oper. Res.*, vol. 4, no. 2, pp. 109–123, 1997. https://doi.org/10.1111/j.1475-3995.1997.tb00068.x
[51] R. M. Quaiser and P. R. Srivastava, “Outbound open innovation effectiveness measurement between big organizations and startups using Fuzzy MCDM,” *Manag. Decis.*, 2024. https://doi.org/10.1108/md-07-2022-0990
[52] M. Weck, I. Humala, P. Tamminen, and F. A. F. Ferreira, “Knowledge management visualisation in regional innovation system collaborative decision-making,” *Manag. Decis.*, vol. 60, no. 4, pp. 1017–1038, 2021. https://doi.org/10.1108/MD-01-2021-0064
[53] A. Mardani, A. Jusoh, K. Nor, Z. Khalifah, N. Zakwan, and A. Valipour, “Multiple criteria decision-making techniques and their applications – A review of the literature from 2000 to 2014,” *Econ. Res.-Ekon. Istraz.*, vol. 28, no. 1, pp. 516–571, 2015. https://doi.org/10.1080/1331677X.2015.1075139
[54] A. Kolios, V. Mytilinou, E. Lozano-Minguez, and K. Salonitis, “A comparative study of multiple-criteria decision-making methods under stochastic inputs,” *Energies*, vol. 9, no. 7, p. 566, 2016. https://doi.org/10.3390/EN9070566
[55] I. U. Hassan and S. Asghar, “A framework of software project scope definition elements: An ISM-DEMATEL approach,” *IEEE Access*, vol. 9, pp. 26 839–26 870, 2021. https://doi.org/10.1109/ACCESS.2021.3057099
[56] A. Kumar and D. V. Singh, “Overview of interpretive structural modeling,” *Int. J. Eng. Appl. Sci. Technol.*, vol. 4, no. 5, pp. 536–540, 2019. https://doi.org/10.33564/ijeast.2019.v04i05.078
[57] Z. Ashtianipour and H. Zandhessami, “An integrated ISM-DEMATEL model for evaluation of technological innovation capabilities' impact on the competitiveness of Small & Medium Size Enterprises (SMEs),” in *2015 Portland International Conference on Management of Engineering and Technology (PICMET)*, Portland, OR, USA, 2015, pp. 322–334. https://doi.org/10.1109/PICMET.2015.7273092
[58] Y. Chen, R. Zhou, and Y. Zhou, “Analysis of critical factors for the entrepreneurship in industries of the future based on DEMATEL-ISM approach,” *Sustainability*, vol. 14, no. 24, p. 16812, 2022. https://doi.org/10.3390/su142416812
[59] M. Alawamleh, A. Al-Twal, L. Lahlouh, and R. O. Jame, “Interpretive structural modelling of organizational innovation factors: An emerging market perspective,” *J. Open Innov. Technol. Mark. Complex.*, vol. 9, no. 2, p. 100067, 2023. https://doi.org/10.1016/j.joitmc.2023.100067
[60] United Nations ECLAC and Subregional Headquarters for the Caribbean, “Study on the vulnerability and resilience of Caribbean Small Island Developing States (SIDS),” 2011, UN Symbol: LC/CAR/L.354. https://hdl.handle.net/11362/38568
[61] N. Khan, “Critical review of sampling techniques in the research process in the world,” *SSRN Electron. J.*, 2020. https://doi.org/10.2139/ssrn.3572336
[62] X. Y. Wang, “Use of proper sampling techniques to research studies,” *Appl. Comput. Eng.*, vol. 57, pp. 141–145, 2024. https://doi.org/10.54254/2755-2721/57/20241324
[63] M. D. C. Tongco, “Purposive sampling as a tool for informant selection,” *Ethnobot. Res. Appl.*, vol. 5, pp.

147–158, 2007. https://doi.org/10.17348/era.5.0.147-158

[64] D. Sirimewan, A. Samaraweera, N. Manjula, R. Rameezdeen, M. Rodrigo, and E. Ekanayake, "Strategies for sustainable irrigation system management: A socio-technical system approach," *Eng. Constr. Archit. Ma.*, vol. 30, no. 2, pp. 436–455, 2023. https://doi.org/10.1108/ECAM-06-2021-0521

[65] S. I. Zaman, S. A. Khan, S. Qabool, and H. Gupta, "How digitalization in banking improve service supply chain resilience of e-commerce sector? A technological adoption model approach," *Oper. Manag. Res.*, vol. 16, no. 2, p. 904–930, 2023. https://doi.org/10.1007/s12063-022-00341-0

[66] S. Jharkharia and R. Shankar, "IT-enablement of supply chains: Understanding the barriers," *J. Enterp. Inf. Manag.*, vol. 18, no. 1, pp. 11–27, 2005. https://doi.org/10.1108/17410390510571466

[67] S. Jharkharia and R. Shankar, "Developing interconnection matrices in structural modeling," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-4, no. 1, p. 81–87, 2005. https://doi.org/10.1109/TSMC.1974.5408524

[68] R. Attri, N. Dev, and V. Sharma, "Interpretive structural modelling (ISM) approach: An overview," *Res. J. Manag. Sci.*, vol. 2, no. 2, pp. 3–8, 2013.

[69] J. Ferreira and A. Coelho, "Dynamic capabilities, managerial and marketing capabilities and their impact on the competitive advantage and firm performance," *Int. J. Entrep. Small Bus.*, vol. 30, no. 4, pp. 629–652, 2017. https://doi.org/10.1504/IJESB.2017.082925

[70] C. E. Helfat and J. A. Martin, "Dynamic managerial capabilities: Review and assessment of managerial impact on strategic change," *J. Manag.*, vol. 41, no. 5, pp. 1281–1312, 2015. https://doi.org/10.1177/0149206314561301

[71] S. A. Keelson, J. Cúg, J. Amoah, Z. Petráková, J. O. Addo, and A. B. Jibril, "The influence of market competition on SMEs' performance in emerging economies: Does process innovation moderate the relationship?" *Economies*, vol. 12, no. 11, p. 282, 2024. https://doi.org/10.3390/economies12110282

[72] I. C. Baierle, G. B. Benitez, E. O. B. Nara, J. L. Schaefer, and M. A. Sellitto, "Influence of open innovation variables on the competitive edge of small and medium enterprises," *J. Open Innov. Technol. Mark. Complex.*, vol. 6, no. 4, p. 179, 2020. https://doi.org/10.3390/joitmc6040179

[73] K. Y. Chan, L. A. G. Oerlemans, and T. Pretorius, "A relational view of knowledge transfer effectiveness in small new technology-based firms: An empirical analysis of a South African case," *Afr. J. Bus. Manag.*, vol. 6, no. 11, pp. 3930–3940, 2012. https://doi.org/10.5897/AJBM11.230

[74] R. Torres de Oliveira, S. Gentile-Lüdecke, and S. Figueira, "Barriers to innovation and innovation performance: The mediating role of external knowledge search in emerging economies," *Small Bus. Econ.*, vol. 58, pp. 1953–1974, 2022. https://doi.org/10.1007/s11187-021-00491-8

[75] T. Broome, W. Moore, and P. Alleyne, "Financing constraints and the R&D decision in the Caribbean," *Entrep. Reg. Dev.*, vol. 30, no. 9-10, pp. 964–986, 2018. https://doi.org/10.1080/08985626.2018.1515820

[76] G. I. S. Bolatan, A. Giadedi, and T. U. Daim, "Exploring acquiring technologies: Adoption, adaptation, and knowledge management," *IEEE Trans. Eng. Manag.*, vol. 71, pp. 1950–1958, 2022. https://doi.org/10.1109/TEM.2022.3168901

[77] M. Ghobakhloo and N. T. Ching, "Adoption of digital technologies of smart manufacturing in SMEs," *J. Ind. Inf. Integr.*, vol. 16, p. 100107, 2019. https://doi.org/10.1016/j.jii.2019.100107

[78] I. Shyle and E. Rruplli, "Implementation of Industry 4.0 challenges in developing countries: A case study of Albania," in *Proceedings of the Joint International Conference: 10th Textile Conference and 4th Conference on Engineering and Entrepreneurship*, Tirana, Albania, 2024, pp. 12–23. https://doi.org/10.1007/978-3-031-48933-4_2

[79] S. Erişen, "An empirical study of the technoparks in turkey in investigating the challenges and potential of designing intelligent spaces," *Sustainability*, vol. 15, no. 13, p. 10150, 2023. https://doi.org/10.3390/su151310150

[80] B. Bhatnagar, V. Dörfler, and J. MacBryde, "Navigating the open innovation paradox: An integrative framework for adopting open innovation in pharmaceutical R&D in developing countries," *J. Technol. Transf.*, vol. 48, no. 6, pp. 2204–2248, 2023. https://doi.org/10.1007/s10961-022-09958-6

Appendix 1. Summary of recent research on Open Innovation (OI) and Industry 4.0 (I4.0) technology adoption

No.	Article	Region/ Country	Industry Focus	I4.0 Technology	Open Innovation Enabling Factors	Open Innovation Barriers	Interaction/ Relationship Observed	Methodology	Policy/ Practical Implications
01	[43]	Malaysia	Retail	Augmented Reality (AR) Technology	Perceived Usefulness; Attitude Towards Use; Competitive and Customer Pressure; Knowledge; Support for Open Business Models	Perceived Cost; External Support and Trading Partner Pressure; Need for Enhanced After-Sales Services	Attitude mediates the relationship between Perceived Usefulness and Behavioural Intention, and between Self-Efficacy and Behavioural Intention; Cognitive and Open Innovation Factors enhance the TAM for AR technology adoption	Survey Data Collection: 233 retail stores in Malaysia; PLS-Based Structural Equation Modelling: Used for data analysis to validate the extended TAM model; Conceptual Model Development: Integrated TAM with open innovation constructs	Managers should offer after-sales services and free installation packages to address operating costs; Retail stores should develop open business models based on cognitive and innovation factors to enhance AR technology diffusion
02	[48]	Not region -specific	Broad industry scope	Industry 4.0 technologies	Cooperation between academia, industry, and governments (Triple Helix model); Ecosystems for technology transfer; Combining I4.0 technologies with open innovation for cost and time efficiency	Limited insights and frameworks for effectively executing I4.0 technology transfer; Challenges in aligning ecosystem components for optimal cooperation	Collaboration among technology recipients, agents, and inventors is essential for successful I4.0 technology transfer	Systematic literature review to analyze and critique existing models and variables for I4.0 technology transfer	Policies should focus on fostering cooperation, strengthening ecosystems, and identifying targeted government support for accelerating I4.0 adoption via technology transfer
03	[41]	Indonesia	SMEs across multiple sectors		Digital Ecosystem Readiness; Knowledge Management; Government Role; Private Sector Role	Digital Equipment Accessibility	A strong relationship between digital ecosystem readiness and open innovation adoption; Knowledge management supports successful implementation of open innovation; Disparities in access to digital equipment contribute to a digital divide, affecting adoption across regions and between SMEs and large firms	Literature Review: Analyzed 32 sample papers using content analysis; Sentiment Analysis: Text mining techniques classified public sentiment (positive, neutral, negative) toward Industry 4.0 in Indonesia	Policymakers should focus on improving the digital ecosystem and ensuring equitable access to digital tools for SMEs; Emphasize knowledge management strategies for SMEs; Support local businesses and SMEs through regulatory measures to ensure fair competition; Address the digital divide between urban and rural areas and between large and small businesses

Appendix 1. Summary of recent research on Open Innovation (OI) and Industry 4.0 (I4.0) technology adoption

No.	Article	Region/ Country	Industry Focus	I4.0 Technology	Open Innovation Enabling Factors	Open Innovation Barriers	Interaction/ Relationship Observed	Methodology	Policy/ Practical Implications
04	[80]	India	Pharma-ceutical sector	Not explicitly stated; the focus is on open innovation strategies rather than specific Industry 4.0 technologies	Selective Use of Open Innovation; Adaptation of Global Best Practices	Open Science Norms; Weak Technology Transfer Systems; Mistrust Between Universities and Industry	Resolution Strategies: Balance between intellectual property protection and openness; Coping Processes: Strategies employed by firms to address OIP challenges	Case Study Evidence: Based on eight Indian pharmaceutical firms; Literature Review and Global Practices: To develop the integrative framework; Conceptual Framework Development: Focused on resolving OIP in developing countries	Guidelines for Adoption: Offers strategies for uplifting open innovation in pharmaceutical sectors of developing countries; Framework Applicability: Valuable for accelerating innovation in similar industries globally
05	[42]	United States	General, with emphasis on industrial R&D	Not explicitly mentioned	R&D spending by SMEs; National innovation capacity; External knowledge	Lower absorptive capacity; Difficulty in identifying and modifying external knowledge; Limited partnership appeal of SMEs; Lack of institutionalized innovation processes -Weak value capture mechanisms	The structural deficiencies of SMEs limit their ability to fully participate in open innovation despite increased R&D spending and importance in national systems	Analysis of trends in R&D spending (1981-2005), comparison of SMEs and large firms	Policymakers should create initiatives to enhance SME absorptive capacity, foster partnerships with academia, and ensure SMEs can capture value from innovation
06	[39, 42]	United States	Broad industry scope	Not explicitly mentioned	Knowledge flows across organisational boundaries; Business model (oriented to openness); Cooperation; Availability and mobility of specialists	Absorption capacity; Multiplication ability; ICT; IP (Intellectual Property)	Distributed innovation processes depend on effectively managed knowledge flows aligned with an organization's business model	Review of academic literature and progress since 2003, including conceptual critiques and future research directions	Research should prioritize conceptual consistency, align open innovation practices with business models, and address gaps in the academic discourse

Appendix 1. Summary of recent research on Open Innovation (OI) and Industry 4.0 (I4.0) technology adoption

No.	Article	Region/ Country	Industry Focus	I4.0 Technology	Open Innovation Enabling Factors	Open Innovation Barriers	Interaction/ Relationship Observed	Methodology	Policy/ Practical Implications
07	[45]	Valle del Cauca, Colombia	Public policy related to Competitive -ness, Science, Technology, and Innovation (CSTI)	Not explicitly mentioned	Actor Networks; Public Policy Support	Limited Depth in Relations: Need to evolve from breadth (wide connections) to depth (stronger, meaningful interactions); Heterogeneous Actor Challenges: Managing diverse stakeholders effectively in public policy contexts	Network Dynamics: Relationships between innovation actors analyzed in terms of breadth and depth; Heterogeneous Actors: Interactions between diverse stakeholders critical for CSTI policy effectiveness	Network Methodology: Analyzes the structure and dynamics of innovation actor networks in the CSTI policy; Case Study: Focuses on Valle del Cauca's regional CSTI policy and its implications for open innovation	Policy Recommendations: Strengthen actor relationships by fostering depth in interactions; Regional Development: Insights for improving the management of CSTI policies and open innovation networks in developing regions
08	[79]	Turkey	Technology Development Zones (TDZs), including universities, technoparks, and smart system projects.	IoT Smart Systems; Machine Learning; AI	Universities and Technopoles: Encouraging IoT and smart system experimentation; Performance Indicators: Incentives and investments for innovation; Global Inspiration: Learning from Silicon Valley's success story	Minority of Design Staff: Limited skilled workforce for intelligent space development; Lack of Innovation: Challenges in fostering innovation within creative organizations; Resource Constraints: Need for incentives and investments	Collaboration Between TDZs and Smart Systems: Performance indicators and incentives drive innovation; Intelligent Spaces and Sustainability: Open innovation enhances sustainable and responsible development in technopoles	Comprehensive Survey: Examines Silicon Valley's development and its application to Turkish TDZs; Empirical Research: Uses AI and machine learning models to evaluate performance indicators; Case Analysis: Evaluates Turkey's TDZ challenges and potential	Recommendations for TDZs: Proposes specific implementations for developing intelligent spaces in new and existing technoparks; Focus on Responsible Innovation: Emphasizes sustainable innovation in technopoles; Encouraging Investments: Highlights critical incentives
09	[46]	Singapore	Family-owned enterprises	Not explicitly stated	Family and business culture; Access to external funds; Government-supported initiatives; Market dynamics; Partnerships and networks; Family capital and external networks	Conservative organizational mindset; High risk aversion; Potential reluctance to adopt ecosystem -based innovation management practices	Key drivers of open innovation in family enterprises are both internal (family capital, culture) and external (partnerships, market dynamics, government support), fostering novel ideas and profitability.	Analysis of a sample of 33 Singapore-based family-owned firms	Highlighted the necessity for managers to combine internal innovation capabilities with environmental determinants to enhance competitiveness and radical innovation generation

Appendix 1. Summary of recent research on Open Innovation (OI) and Industry 4.0 (I4.0) technology adoption

No.	Article	Region/ Country	Industry Focus	I4.0 Technology	Open Innovation Enabling Factors	Open Innovation Barriers	Interaction/ Relationship Observed	Methodology	Policy/ Practical Implications
10	[40]	Vietnam	General business and organizational innovation, emphasizing firms in developing economies	Not directly mentioned	Absorptive Capacity; External Knowledge; R&D Capability; Dynamic Managerial Capabilities	Knowledge Base Gaps: Limited understanding of knowledge accumulation processes in developing countries; Resource Constraints: Challenges in effectively integrating external knowledge with local conditions	Knowledge Dimensions and Innovation: Absorptive capacity influences knowledge breadth and depth; R&D and Innovation: R&D mediates the relationship between external knowledge acquisition and exploratory innovation; Knowledge Depth: Supports both exploratory and exploitative innovation	Model Development: Proposes relationships among absorptive capacity, knowledge dimensions, R&D, and innovation types; Empirical Testing: Uses structural equation modeling (SEM) to analyze survey data from Vietnamese firms	Acquire and Develop Model: Firms should acquire external technologies and enhance R&D to adapt these technologies for local use; Capability Building: Focus on developing organizational-specific capabilities for both exploratory and exploitative innovation
11	[44]	India	Food system, including startups, food value chains, and traditional sectors in developing countries	Innovations in food value chains and startup-driven technological advancements	Startups and Venture Capital; Business Partnerships; Knowledge Flows: Outbound, inbound, and bi-directional exchange of expertise	Infrastructure Deficits: Gaps in food value chains; Traditional Sectors: Limited historical presence of open innovation; Complex Web of Interactions: Challenges in managing interconnected partnerships and knowledge flows	Startups and Stakeholders: Strong interconnections with companies, traders, e-commerce, governments, and international institutions; Knowledge Exchange: Dynamic, bi-directional flows of knowledge among actors enhance food system innovation	Database Analysis: Examines a large database of startups in India's food system; Classification of Startups: Categorized based on their primary functions and interventions in food value chains; Network Analysis: Explores the web of relationships	National Food Policy Recommendations: Internalize innovations for inclusion in the food system; Collaboration Models: Call for rigorous research on business models and agreements between startups, universities, companies, and government agencies

Appendix 1. Summary of recent research on Open Innovation (OI) and Industry 4.0 (I4.0) technology adoption

No.	Article	Region/ Country	Industry Focus	I4.0 Technology	Open Innovation Enabling Factors	Open Innovation Barriers	Interaction/ Relationship Observed	Methodology	Policy/ Practical Implications
12	[78]	Albania	General industries, organisations undergoing digital transformation to adopt Industry 4.0	Cloud Systems; IoT; Cybernetics	Digital Trust; Digital Transformation; Social and Organizational Changes: Support through structural transformations	Challenges in Digitalization: Difficulty in aligning with technological and organizational needs; Implementation Obstacles: Hurdles specific to Albania and other developing countries	Digital Trust fosters open innovation in Industry 4.0 adoption; Digitalization supports social and organizational innovation, emphasizing the integration of consumer-centric services	Survey Data Analysis: Collected from various companies to evaluate Industry 4.0 implementation levels and challenges; Literature Review: Analysis of digitalization and organizational changes supported by prior studies	Strategies to address barriers to Industry 4.0 adoption in developing countries; Emphasis on secure and consumer-oriented digital transformation; Encouragement for social and technological innovations through organizational and policy reforms
13	[47]	Global perspective, with implications for various countries addressing innovation challenges during the COVID-19 pandemic	Broad focus, with relevance to healthcare, government policy, education, research institutions, and private sector collaboration	Not explicitly detailed	Effective Collaboration and Communication; Policy Development; Awareness of Innovation's Role	Economic Crisis Context; Coordination Challenges	Collaboration and Innovation Link: Strong correlation between effective OI practices and pandemic response success; Innovation as a Driver: Identifies emerging hotspots linking technology adaptation, sustainability, healthcare, and economic performance	Systematic Literature Review: Analysis of 218 studies on innovation during the COVID-19 pandemic Framework Development: Based on aggregate components like technology adoption, sustainable development, healthcare, and economic performance	Framework for Research and Practice: Guides future research and policy development in innovation; COVID-19 as an Opportunity: Frames the pandemic as a chance to enhance innovation's role in business and society; Research Hotspots: Identifies critical innovation areas