

Classification of Thailand's industrial firms under global supply chain disruptions: Integrating resilience and sustainability in industrial performance

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Abstract

There has been significant disruption of global supply chains as a result of pandemics, geopolitical tensions, and climate-related events. Firms around the world, including those in Thailand, have been compelled to adapt, with increasing emphasis on resilience and sustainability. While many studies have addressed supply chain performance through these lenses, few have focused specifically on the industrial context in Thailand. Moreover, the direction of industrial transformation in response to global challenges remains insufficiently examined. This study addresses these gaps by proposing a comprehensive framework that integrates conventional supply chain performance indicators with resilience and sustainability dimensions. Data were collected from 98 publicly listed industrial firms in Thailand using their 2023 annual reports. Principal component analysis (PCA) was used to identify key performance patterns, and this was followed by K-means clustering to classify firms based on strategic orientation. The analysis revealed four distinct clusters. The largest group, referred to as resilient enterprises (54 firms), demonstrated a balanced performance across efficiency and resilience. Performance-oriented firms (23 firms) exhibited high customer satisfaction, product quality, and flexibility. Agile and lean operators (6 firms) prioritized operational speed and rapid delivery. Flexibility-centric firms (16 firms) focused on adaptability but faced constraints in financial and inventory performance. Overall, the findings indicate that economic factors such as revenue, profitability, and productivity, together with resilience attributes like agility and flexibility, are the primary variables that differentiate firms. This suggests that Thailand's industrial firms currently place the most emphasis on operational efficiency and adaptability, while broader environmental and social sustainability concerns remain less prominent in strategic differentiation.

Keywords: Supply chain performance, Industrial clustering, PCA, K-means clustering, Thai manufacturing sector

1. Introduction

Recent global disruptions, including pandemics, geopolitical tensions, and climate-related events, have exposed critical weaknesses in supply chains, leading to delivery delays, inventory shortages, and limited response capabilities. These challenges highlight the urgent need for supply chain systems that are both resilient and sustainable. A resilient supply chain ensures adaptability and responsiveness to unforeseen shocks, while a sustainable supply chain emphasizes environmental stewardship, social responsibility, and long-term resource efficiency. Thailand's industrial sector is undergoing a structural shift in response to global market volatility, digital innovation, and rising demands for sustainability and resilience [1]. Recent disruptions have also shifted the focus beyond economic growth, emphasizing the need for supply chain systems that are both robust and environmentally responsible, in order to maintain industrial competitiveness in an uncertain global context [2].

Performance measurement serves as a critical tool for assessing dynamic supply chain conditions. Traditional frameworks, which focus primarily on cost efficiency and operational productivity, are becoming less useful in today's globally interconnected and disruption-prone environment. Addressing current challenges requires more comprehensive approaches that incorporate resilience and sustainability [3]. Despite growing academic interest in supply chain resilience and sustainability, empirical studies that classify firms based on integrated performance profiles remain limited.

Understanding Thailand's industrial shift in response to current challenges requires analytical approaches that capture firm heterogeneity and strategic variation. Clustering is a well-established method for identifying patterns within complex industrial systems [4] and systematically grouping firms with similar characteristics, behaviors, or supply chain orientations. When applied to performance indicators, clustering reveals how firms are aligned along resilience and sustainability dimensions [5], offering valuable insights into industrial trends. However, in the context of Thailand, empirical studies, particularly those that assess performance indicators tailored to local industrial structures and incorporate resilience and sustainability perspectives, remain limited. Moreover, Thailand's industrial transformation in response to these global challenges remains insufficiently understood, especially regarding whether firms are prioritizing resilience, sustainability, or other dimensions in their supply chain adaptations. This gap forms the central

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research problem of this study, which seeks to classify industrial firms using an integrated framework to reveal their strategic orientations amid global supply chain disruptions.

Given the limited empirical research on performance indicators that integrate resilience and sustainability and are suited to Thailand's industrial context, this study adopts a multidimensional framework combining traditional, sustainability-related, and resilience-oriented metrics. Indicators are derived from the relevant literature and were then validated by experts using the Content Validity Ratio (CVR). Supply chain performance data from publicly listed Thai companies are analyzed using Principal Component Analysis (PCA) to reduce dimensionality and reveal latent patterns. K-means clustering is then performed to group firms with similar strategic orientations. This combined approach enhances the interpretation of industrial heterogeneity and supports robust classification under complex supply chain conditions. The study contributes by presenting an empirical classification of Thailand's industrial firms that integrates these dimensions and provides insights to guide both theoretical understanding and practical strategies for balancing resilience and sustainability. It focuses on classifying firms according to their performance patterns, and exploring whether they prioritize resilience, sustainability, or other adaptive strategies in response to global disruptions.

2. Supply chain management and performance assessment

Industrial supply chain management (SCM) involves the strategic coordination of activities ranging from the procurement of raw materials and in-process manufacturing to the distribution of finished goods to consumers. This integrated process includes procurement, production, logistics, inventory management, and transportation. Effective SCM requires collaboration among stakeholders such as suppliers, manufacturers, logistics providers, distributors, retailers, and end customers. The collective goal is to streamline operations, improve efficiency, and enhance value creation across the entire chain [6]. In the digital era, SCM systems must ensure the timely and accurate delivery of goods while minimizing risks and optimizing flows across digital supply networks [7].

The role of SCM has become increasingly critical, particularly in influencing economic performance, responsiveness, and reliability. Economically, well-managed supply chains reduce the costs of production, inventory, and transportation, contributing to stronger financial outcomes [8, 9]. Responsiveness is supported by real-time data-sharing across supply chain partners, enabling immediate decision-making and faster delivery to customers [10]. Enhanced visibility allows firms to respond more quickly to customer orders. In addition, reliability ensures the consistent and accurate delivery of goods, which is essential for maintaining customer satisfaction and building long-term trust. Reliable supply chains also facilitate better planning and forecasting [11].

Recent studies have emphasized the need to evaluate supply chain performance by considering these dimensions collectively. For instance, Ebrahimi and Bagheri [12] proposed a network model for the energy sector that assesses both fuel cost and processing facility reliability. Keskin and Ungan [10] examined factors influencing responsiveness and the link from responsiveness to customer satisfaction and competitive advantage in Turkey. Pu et al. [13] explored the impact of supply chain quality management on reliability, highlighting the importance of adaptability.

Emerging concepts such as supply chain resilience and agility further expand the scope of performance evaluation. Reliability focuses on consistent performance under normal conditions, while resilience emphasizes the ability to adapt to and recover from disruptions, including supply shortages, geopolitical issues, and natural disasters [14]. Resilient supply chains prioritize business continuity and long-term adaptability. Agility, in this context, refers to flexibility and rapid responsiveness to changing demand or market conditions [15].

Sustainability in the supply chain adds another essential layer by addressing environmental impact, social equity, and economic viability. Sustainable supply chain practices contribute to global efforts such as the Sustainable Development Goals (SDGs), particularly SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production), and SDG 13 (climate action) [16, 17]. A holistic sustainability approach allows businesses to meet their customers' expectations while contributing to broader societal and environmental objectives. Recent research has applied sustainability concepts to diverse sectors including industrial goods, healthcare, food, and energy [18, 19].

To improve supply chain performance in terms of resilience and sustainability, firms must understand their strategic positioning within broader industrial clusters. These clusters influence how firms structure and manage their supply chains and shape their competitive advantages in the face of global disruptions. In Thailand, where global supply chain shifts have created new pressures for industrial adaptation, understanding firm positioning is especially important for maintaining competitiveness. However, there remains a lack of empirical studies focusing specifically on Thailand's industrial context, and the integration of resilience, sustainability, and traditional supply chain performance has not been extensively analyzed. This study contributes to filling that gap by using actual industrial data to classify Thai firms based on their performance dimensions. The analysis helps reveal how these firms position themselves strategically and adapt to evolving supply chain challenges.

3. Methodology

Figure 1 illustrates the methodological framework, which is organized into three sequential phases.

3.1 Factor selection and data collection phase

The first step involved identifying relevant performance indicators through an extensive review of the literature on supply chain performance, resilience, and sustainability. These indicators were refined through expert interviews, during which specialists in logistics and supply chain management assessed their relevance to the Thai industrial context. Reliability and validity are essential to ensure that the selected performance indicators accurately represent the constructs that are being studied. The CVR is a method widely used in research to assess the appropriateness and content validity of performance indicators, ensuring that the selected measures accurately represent the constructs (e.g., [20-22]). Following this approach, this study employed the CVR to validate the indicators after their review by the experts, ensuring alignment with both the theoretical and the practical aspects.

Following the factor validation, data were collected from publicly listed Thai industrial firms, which are required to publish standardized annual reports online. Performance data for the 2023 fiscal year were extracted from these reports, providing consistent financial and operational information. When data were missing or unclear, additional details were obtained through structured interviews with company representatives to ensure accuracy and completeness. The resulting dataset offers a comprehensive overview of Thailand's industrial performance and served as the input for the subsequent analyses.

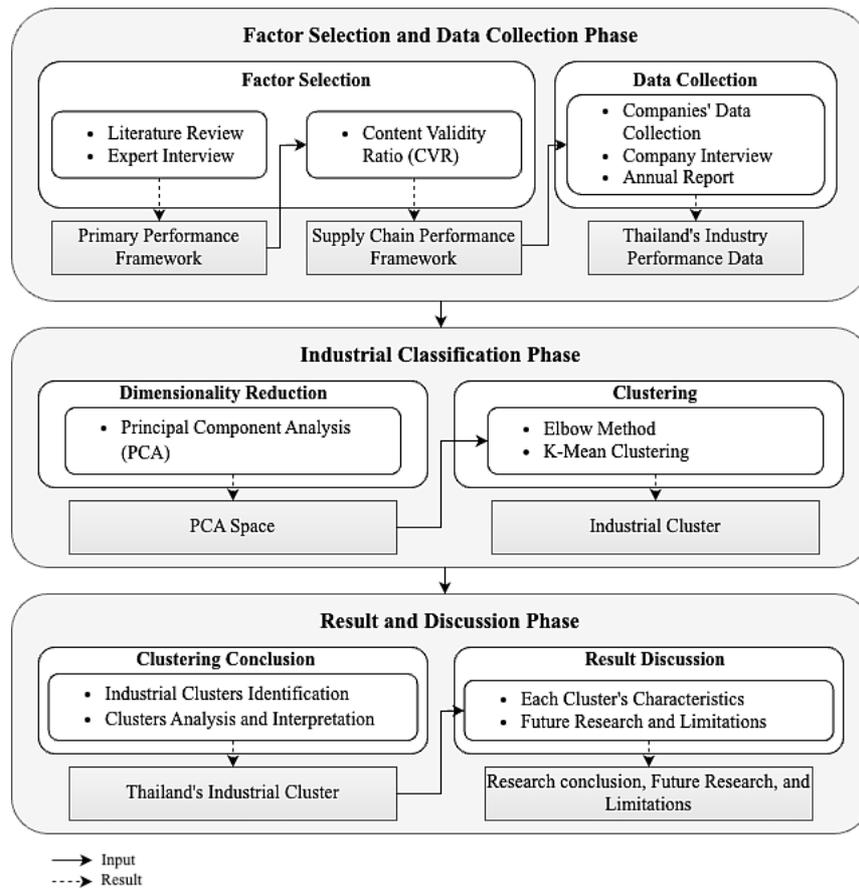


Figure 1 Methodological framework

3.2 Industrial classification phase

In the second phase, the dataset was analyzed using Principal Component Analysis (PCA) in R programming to reduce the number of variables and reveal underlying performance patterns. PCA has been widely used in prior supply chain and industrial studies for performance evaluation and classification because it effectively condenses multidimensional data into interpretable components without significant information loss [23-26]. It was selected here to summarize the variance and to generate component scores suitable for clustering, in order to achieve the study's goal of identifying performance patterns.

The K-means clustering algorithm was subsequently applied, also in R programming, to group firms based on their principal component scores. The optimal number of clusters was determined using the Elbow Method, which evaluates the within-cluster sum of squares across multiple cluster solutions. K-means has been widely used in classification studies to identify strategic groupings because it is able to generate clear and interpretable clusters, particularly in large datasets [26-29]. This method was chosen because it efficiently distinguishes performance groups and is well-suited to the study's objective of identifying strategic orientations within Thailand's industrial sector.

3.3 Result interpretation and discussion phase

The resulting clusters were analyzed to interpret their strategic positioning, with a focus on resilience, sustainability, and traditional performance indicators. Descriptive statistics and comparative profiles were used to highlight key differences among the clusters and identify operational and strategic trade-offs.

Finally, the clustering results were synthesized to provide insights into how Thai industrial firms respond to global supply chain disruptions. Policy and managerial implications were considered, with an emphasis on the integration of resilience and sustainability into supply chain strategies. The study's limitations, and recommendations for future research, were also addressed.

4. Results

4.1 Supply chain performance framework for Thailand's industrial companies

This study classifies Thailand's industries by examining their supply chain performance through two overarching dimensions: sustainability and resilience. The sustainability dimension comprises economic, environmental, and social sub-aspects. The economic sub-aspect reflects traditional supply chain performance and includes factors such as cost efficiency, profitability, and productivity, which together indicate the operational and financial effectiveness of a firm. The environmental sub-aspect captures sustainability in terms of resource utilization, and particularly energy consumption. The social sub-aspect addresses stakeholder well-being and corporate social responsibility, encompassing aspects such as customer satisfaction, employee welfare, and workplace safety. Complementing these, the resilience dimension reflects a firm's capacity to adapt to and recover from disruption, encompassing key

attributes such as flexibility, agility, and robustness. Tables 1 and 2 outline the performance indicators and the sub-criteria derived from them; these serve as the input variables for clustering the Thai companies on the basis of their supply chain characteristics.

4.2 Thailand's clusters of industrial companies

Figure 2 illustrates the PCA, combined with the K-means clustering, by mapping the firms onto a two-dimensional space defined by the first two principal components. Each colored point represents a firm, with clustering determined by multidimensional similarity. Four distinct clusters emerge, reflecting different strategic orientations across the industrial landscape.

Table 1 Summary of supply chain performance factors (Sustainability aspect)

Sub-aspect	Factors	Short description	Measurement	Unit
Economy	Cost (X1)	The total expenses incurred in operations, including raw materials, labor, and logistics. [30, 31]	Company cost in the past year	10 million Baht
	Time (X2)	The duration required for processes, including production, transportation, and delivery. [32, 33]	Delivery time to customers	Days
	Quality (X3)	The standard of products and services measured by defect rates and compliance with specifications. [34, 35]	Order fulfillment capability in the past year	%
	Profitability (X4)	The financial gain after expenses, indicating business sustainability and competitiveness. [36, 37]	Company net profit in the past year	10 million Baht
	Productivity (X5)	The efficiency of resource utilization to maximize output per unit of input. [38, 39]	Employment rate in the past year	1,000 people
Environment	Energy Consumption (X6)	The amount of energy used in operations, affecting sustainability and cost efficiency. [40, 41]	Total energy consumption in the past year	100,000 kWh
Social	Customer Satisfaction (X7)	The level of fulfillment experienced by customers based on service quality and product performance. [42, 43]	Customer satisfaction score (scale of 1 to 10)	Score
	Noise Pollution (X8)	The impact of operational activities on the surrounding environment in terms of sound levels. [44]	Average noise level in the factory	dB
	Employment Satisfaction (X9)	The well-being and job contentment of employees, impacting productivity and retention. [45, 46]	Employee satisfaction score (scale of 1 to 10)	Score
	Health and Safety (X10)	Workplace conditions that ensure employee well-being, reducing accidents and health risks. [47, 48]	Number of workplace accidents in the past year	Number

Table 2 Summary of supply chain performance factors (Resilience aspect)

Sub-aspect	Factors	Short description	Measurement	Unit
Flexibility	Supplier Flexibility (X11)	The ability of suppliers to adapt to changes in demand, production needs, and disruptions. [37]	Time for supplier deliveries	Days
Agility	Cash-to-Cash Cycle (X12)	The time taken between cash outflows for raw materials and cash inflows from customer payments. [38, 49]	Time from raw material payment to customer payment receipt	Days
Robustness	Inventory Health (X13)	The ability to maintain optimal inventory levels to prevent shortages or excess stock. [50, 51]	Percentage of inventory ready for use	%
	Perfect Delivery Rate (X14)	The percentage of deliveries completed on time, in full, and without errors. [52, 53]	On-time and error-free delivery rate	%

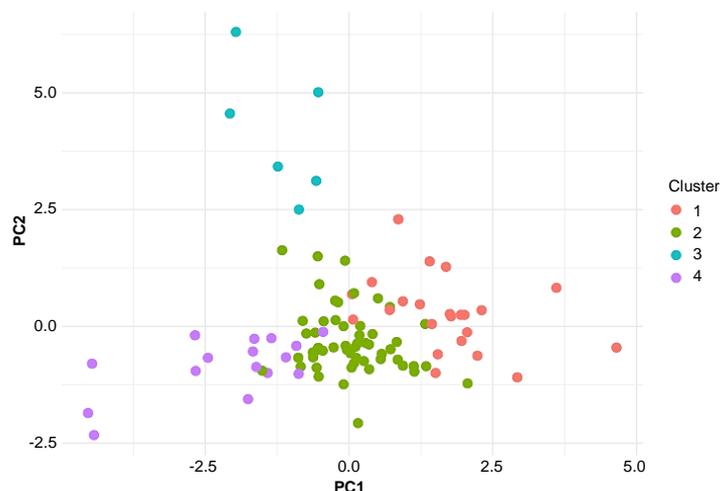


Figure 2 Clustering of Thailand's industrial companies using PCA and K-means clustering

Tables 3 and 4 present a classification of the companies into four clusters based on their supply chain performance characteristics, with Table 4 showing the cluster-wise arithmetic means for each variable; shaded cells denote the most desirable value for each factor. The clustering analysis identified four distinct groups of firms, each with a characteristic supply chain performance pattern and strategic orientation.

Table 3 Clusters of companies based on their supply chain performance characteristics

Cluster	Cluster Name	Characteristic	Number of companies
1	Performance-Oriented Firms	High satisfaction, quality and flexibility	23
2	Resilient Enterprises	Balanced performance with high efficiency and resilience	54
3	Agile and Lean Operators	Speed-focused, lean operations with high delivery performance	6
4	Flexibility-Centric Firms	Highly flexible but financially constrained supply chains	16

Table 4 Mean values of performance factors by cluster

Cluster		1	2	3	4
Cluster Name and Units		Performance-Oriented Firms	Resilient Enterprises	Agile and Lean Operators	Flexibility-Centric Firms
X1	10 million Baht	9,642.44	6,168.20	79,310.88	4,317.76
X2	Days	14.22	4.41	4.31	3.38
X3	%	96.72	95.94	98.17	98.31
X4	10 million Baht	-314.24	577.42	2314.68	688.04
X5	1,000 people	3,817.87	6,154.13	13,227.87	7,920.00
X6	100,000 kWh	79.91	77.13	76.25	68.62
X7	Score	8.56	8.18	8.67	8.51
X8	dB	8,542.79	3,569.10	64,681.48	948.68
X9	Score	7.97	8.15	7.80	8.99
X10	Number	4.36	6.35	186.17	5.19
X11	Days	31.09	12.50	8.92	4.88
X12	Days	94.35	40.11	53.75	30.64
X13	%	83.26	86.83	88.67	65.14
X14	%	97.04	95.31	95.75	96.19

Cluster 1, Performance-Oriented Firms (23 companies), emphasize service quality, customer satisfaction, and operational flexibility, with high scores for product quality (96.72%) and customer satisfaction (8.56). However, they suffer extended lead times (14.22 days) and long cash-to-cash cycles (94.35 days), and report negative profitability (−314.24 million Baht), indicating inefficiencies that may undermine long-term sustainability.

Cluster 2 companies, Resilient Enterprises (54 companies), demonstrate a balanced profile across efficiency, resilience, and productivity. These firms maintain moderate delivery times (4.41 days), positive profitability (577.42 million Baht), and strong inventory health (86.83%), although they exhibit lower employee satisfaction and occupational safety.

Cluster 3, Agile and Lean Operators (6 companies), outperform other groups in operational speed, output, and profitability. With the highest productivity (13,227.87 units) and product quality (98.17%), these firms operate through streamlined and technology-driven models. However, their high energy usage (76.25 × 100,000 kWh) and frequent order cycles (186.17 times) may raise concerns regarding long-term resource sustainability.

Lastly, Cluster 4, Flexibility-Centric Firms (16 companies), prioritize adaptability and responsiveness, achieving the shortest lead times (3.38 days) and fastest cash flow cycles (30.64 days), while maintaining high customer (8.51) and employee satisfaction (8.99). Despite these strengths, their limited supplier flexibility (4.88 days) and relatively low inventory health (65.14%) present challenges for sustaining performance under supply-side uncertainty.

5. Discussion

The clustering analysis reveals strategic trade-offs by Thailand's industrial firms, reflecting diverse operational priorities. Cluster 1, labeled as performance-oriented, comprises firms engaged in packaging, chemical manufacturing, and engineered wood products. These firms emphasize product quality and customer satisfaction but face extended lead times and prolonged cash-to-cash cycles, consistent with the findings of Hoe and Mansori [54]. Their focus on output and service excellence appears to limit their agility in adapting to market volatility. In contrast, Cluster 4, identified as flexibility-centric, includes firms in the fast-moving consumer goods and commercial property sectors. While these firms demonstrate high flexibility and rapid responsiveness, they encounter difficulties in maintaining quality control and supplier consistency, which is in line with the trade-offs discussed by Frei [55] and Hallavo [56]. Cluster 3, defined as agile and lean operators, consists of large-scale retailers and energy providers. Their high agility and profitability likely stem from streamlined, technology-enabled operations focused on speed and scalability. Lastly, Cluster 2, categorized as resilient enterprises, includes firms engaged in the home improvement sector, food processing, and energy distribution. These firms operate with large workforces and moderate agility, adopting a resilience strategy based on capacity buffers and human resources rather than rapid responsiveness [42, 57, 58].

Although the proposed framework incorporates a comprehensive view of supply chain performance, including economic, environmental, and social aspects of sustainability alongside resilience, the clustering results indicate a stronger emphasis on resilience and traditional performance measures. The primary differentiators among the clusters are financial indicators such as revenue, profitability, and productivity, as well as resilience-related factors such as delivery lead time, cycle time, agility, and supplier flexibility [59]. In comparison, sustainability indicators related to environmental and social dimensions, such as energy consumption, employee satisfaction, and occupational safety, appear less influential in shaping the cluster profiles. This pattern suggests that, while the

conceptual model is aligned with global expectations for sustainable supply chain transformation, Thailand's industrial firms tend, in practice, to be categorized more distinctly by their adaptive capacities and operational efficiencies. This can be explained by the greater variability of economic and resilience indicators across firms, combined with the relatively uniform or compliance-driven reporting of sustainability metrics. Moreover, firms tend to prioritize immediate operational responses to disruptions over longer-term sustainability objectives, which often require sustained investment and policy alignment.

To strengthen the role of sustainability, it is suggested that firms integrate environmental and social metrics into performance evaluations, establish links between these metrics and financial outcomes, and enhance the transparency of sustainability reporting. The adoption of internationally recognized frameworks, such as the SDGs or the Global Reporting Initiative (GRI), and the use of green financing instruments may further support alignment between sustainability initiatives and resilience strategies. Policymakers are encouraged to introduce incentives, including tax benefits, preferential financing, and recognition programs, to motivate corporate investment in sustainable practices [60]. Firms should also balance the pursuit of agility in responding to disruptions with the development of long-term sustainability strategies through comprehensive planning and capacity building [61]. These recommendations highlight a gap between sustainability goals and actual performance, underscoring the need for stronger integration of environmental and social responsibility into supply chain management.

While this study provides important insights into the strategic orientations of Thailand's industrial firms, certain considerations should be noted. The analysis focuses on 99 publicly listed firms selected for their standardized reporting, which may not fully reflect the dynamics of smaller or unlisted firms. Reliance on annual reports ensures consistency but may underrepresent operational challenges, particularly in sustainability and resilience. Cross-country comparisons were not included, as the primary aim was to establish a context-specific classification framework. This study prioritizes clustering to identify performance patterns, providing a foundation for future research to extend the framework to SMEs, to incorporate additional data sources, and to apply methods such as regression or structural equation modeling to examine causal relationships among performance dimensions.

6. Conclusions

This study examined the strategic orientations of 98 publicly listed industrial firms in Thailand. It applied PCA and K-means clustering to a multidimensional framework that combined conventional supply chain performance indicators with resilience and sustainability perspectives. The analysis identified four distinct groups: performance-oriented firms, resilient enterprises, agile and lean operators, and flexibility-centric firms. The findings indicate that Thailand's firms currently place greater emphasis on operational efficiency and adaptive capacity, particularly in terms of agility and flexibility, while environmental and social sustainability receive comparatively less attention. This highlights a tendency to respond to external uncertainty through immediate operational measures rather than long-term sustainable transformation. The methodological approach effectively revealed strategic patterns within complex performance data, offering a structured basis for classifying firms. This research contributes to the literature by introducing an integrated classification approach that combines traditional, resilience, and sustainability dimensions, which have rarely been examined together in prior studies. It advances our understanding of how industrial firms in emerging economies adapt to global disruptions, and provides a methodological example of using PCA and K-means for multidimensional performance analysis. These insights contribute to a better understanding of industrial behavior in the Thai context and have useful implications for policy makers and supply chain strategists seeking to support resilience and competitiveness in a changing global environment.

7. References

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