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Analyzing Global Semiconductors Supply Chain Resilience Using Structural Equation Modeling

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Abstract

The global semiconductor chip shortage has exposed critical vulnerabilities in supply chains, significantly impacting various industries. This study proposes a comprehensive framework to enhance the resilience of semiconductor supply chains by identifying key factors and their interactions. Leveraging Structural Equation Modeling (SEM), the framework integrates fourteen hypotheses to analyze nine different factors affecting the semiconductor supply chain resilience. Artificial Intelligence (AI), supply chain integration, agility, and localization are among the factors analyzed in this study. The model is developed based on insights from literature within the engineering and decision sciences subject areas and is preliminarily tested using secondary data generated based on the literature. Initial results, based on this secondary data, underscore the importance of AI and digital technologies in fostering transparent, agile supply chains, enabling firms to respond swiftly to disruptions. Additionally, manufacturing flexibility and supply chain integration emerged as critical enablers of resilience, ensuring long-term competitiveness in the semiconductor industry. Future research will validate these findings by applying primary survey data on the framework developed in this study to further contribute to the understanding of supply chain resilience in high-tech industries.

Keywords
Semiconductor Chip Shortage, Supply Chain Resilience, Manufacturing Flexibility, AI Integration, Partial Least Squares Structural Equation Modeling (PLS-SEM)

1. Introduction
The global semiconductor chip shortage has emerged as a critical challenge, necessitating a comprehensive understanding of its complexities. Building upon the foundational research presented in "The Global Semiconductor Chip Shortage: Causes, Implications, and Potential Remedies" by Mohammad et al. (2022), this study aims to deepen our understanding of the crisis. Our primary objective is to transition initial findings into a scholarly paper, leveraging an updated literature review and employing statistical analysis to identify effective strategies and remedies.

Recent advancements in semiconductor research underscore the importance of our investigation. Azzoni et al. (2023) highlight the roles of international initiatives and the significance of emerging technologies and digitalization strategies in reshaping supply and value chains, emphasizing the interconnected nature of the global semiconductor landscape. Similarly, the work by Mohammed & Khan (2022) examines the causal factors behind supply chain disruptions during the COVID-19 pandemic, emphasizing the imperative of resilience and providing a framework for analyzing disruptive elements.

Our paper synthesizes these scholarly insights to make substantive contributions to the field. We have developed a robust framework guided by existing literature and expert opinion to discern the factors influencing semiconductor supply chain resilience. Through hypotheses formulation and the use of Partial Least Squares Structural Equation Modeling (PLS-SEM), we test both measurement and structural models using secondary data based on the literature, enabling an in-depth analysis of the relationships among various factors and assessing the model's validity and reliability.

1.1 Objectives

To achieve our research goals, we seek to address the principal factors influencing semiconductor supply chain resilience amidst the current crisis and investigate how these factors interact to impact overall resilience. We also aim to identify strategies and remedies that are most effective in bolstering supply chain resilience and mitigating semiconductor shortages.

By integrating contemporary research insights with advanced statistical analyses, our study aims to devise innovative and practical strategies to address the multifaceted challenges posed by the global semiconductor shortage. Our unique contributions include a comprehensive framework for resilience, empirical validation of influential factors based on secondary data, and actionable recommendations for industry stakeholders.

Accordingly, this conference paper presents the development of the model, preliminary testing based on insights from secondary data from the literature, and outlines the process of applying the model using primary survey data. This work lays the foundation for more comprehensive future research, where the model can be tested on primary survey data to further validate the findings established in this study.

2. Literature Review

The semiconductor chip shortage, exacerbated by digitalization, the COVID-19 pandemic, and increasing technology demand, has significantly impacted various industries, particularly technology, automotive, and healthcare. This crisis has resulted in production delays and heightened costs and underscored the critical role of semiconductors in modern electronics.

Recent literature explores multiple dimensions of this shortage. Mohammad et al. (2022) analyze global semiconductor supply chain shortages, detailing their causes, effects, and potential solutions. In contrast, Hasan et al. (2023) argue that supply chain difficulties do not significantly affect firm output. Mohammed & Khan (2022) address industry-wide supply chain issues, while Jaenichen et al. (2022) model the demand disruptions.

Furthermore, Leslie (2022) examines the economic impact of COVID-19 on the semiconductor industry, and Liu et al. (2024) discuss advancements in 2D electronic materials, while Mohammad et al. (2022) connect existing challenges with future technologies to explore supply chain resilience. In addition, Tziantzioulis et al. (2023) introduce a market-adaptability index and digital twin technologies to formulate comprehensive shortage control plans encompassing policy, management, and technology.

Soto-Ferrari et al (2023) provide forecasts for the automotive sector, while Mohammad et al. (2022) consider how industry-specific advancements can alleviate broader supply chain issues. They synthesize governmental requirements with business practices and technological trends. Additionally, Van Kollenburg et al. (2024) emphasize the utility of predictive discarding, contrasting with the focus of Mohammad et al. (2022) on process efficiency to address the global chip crisis.

2.1 Gap Identification & Research Questions

While the existing literature offers valuable insights into the causes and effects of semiconductor shortages from diverse perspectives, gaps remain in understanding the factors that influence supply chain resilience and in developing effective remedies. This study addresses these gaps by investigating the key factors contributing to semiconductor supply chain resilience and proposing actionable strategies to mitigate the shortage.

Literature on semiconductor supply chain resilience lacks awareness of how internal organizational capabilities and external collaboration practices mitigate supply chain disturbances. Several studies have examined the adoption of advanced technologies, such as AI and digital technology for tracking systems within the context of manufacturing and shipping. However, the link between these organizational innovations and the supply chain has not been adequately studied. This gap in coverage allows for research that connects such sectors to show resilience in high-tech industries.

To achieve this, we will explore the following research questions:

Research Question 1: What are the key factors influencing semiconductor supply chain resilience amid the current crisis, and how do these factors interact to affect overall resilience?

Research Question 2: What are the most effective strategies and remedies for enhancing semiconductor supply chain resilience and mitigating the shortage?

These questions demonstrate that SSRC has several sides by explaining how internal innovation processes and external supply chain relationships interact. These connections could provide theoretical and practical contributions for organizations seeking strategic advantages in a changing market. Additionally, these questions may help people create more focused and successful plans to address the semiconductor industry's current and future difficulties.

3. Methodology

As outlined in the objective section, this paper will present the development of the framework and its testing using secondary data derived from the literature.

The methodology was hence split into two phases, as indicated in Figure 1 and described in the subsequent paragraphs.

Initially, an extensive literature review was conducted to identify updated research findings and research topics within the supply chain shortage research area. A general review within the engineering and decision sciences subject areas aided in identifying key factors influencing the semiconductor supply chain resilience (SSCR). These factors formed the constructs of our model, informing the development of our framework. To evaluate our framework and the effects of the identified factors on SSCR, hypotheses and a survey to test the hypotheses was developed. The survey consisted of a series of 3-4 statements related to each factor, rated on a Likert scale from 'Strongly Disagree' (1) to 'Strongly Agree' (7) to quantify and measure the effects of each factor.

With the primary aim of this paper being to identify factors influencing SSCR and provide a framework for testing the relationship among the factors, our research tested the framework with 200 generated sample inputs based on secondary data from the literature. The generated data was analyzed to assess the effectiveness of our proposed framework using SMART PLS for SEM. Structural Modelling was used to analyze predictive results to assess correlations that inform the acceptance or rejection of the proposed hypotheses, focusing on R-squared values, F-squared values, and path coefficients. The results revealed the strength and validity of the relationship between the identified factors. Discussion and remedies were formulated based on the outcomes our framework generated with the secondary input data (Figure 1).

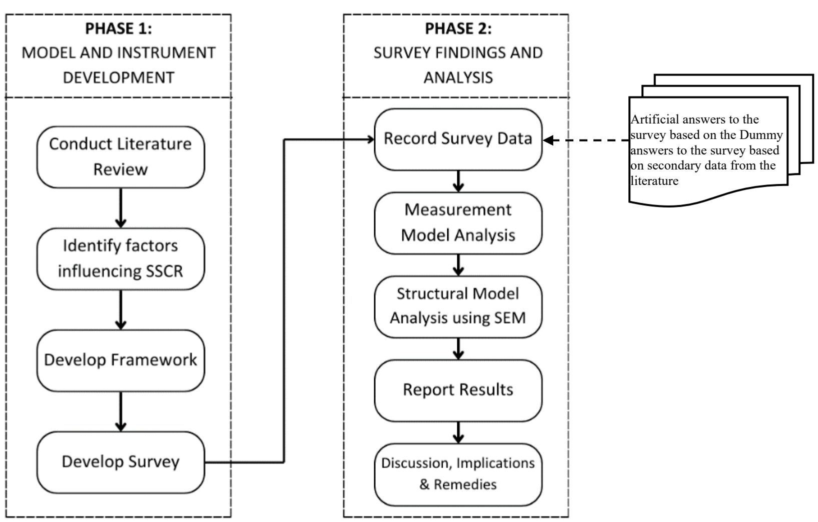

Figure 1. Research methodology

4. Model Development

The semiconductor supply chain shortage has been analyzed extensively in the literature, leading us to develop the framework shown in Figure 2 below, which incorporates critical factors identified from previous studies. The elements of this model are further discussed in the subsequent section.

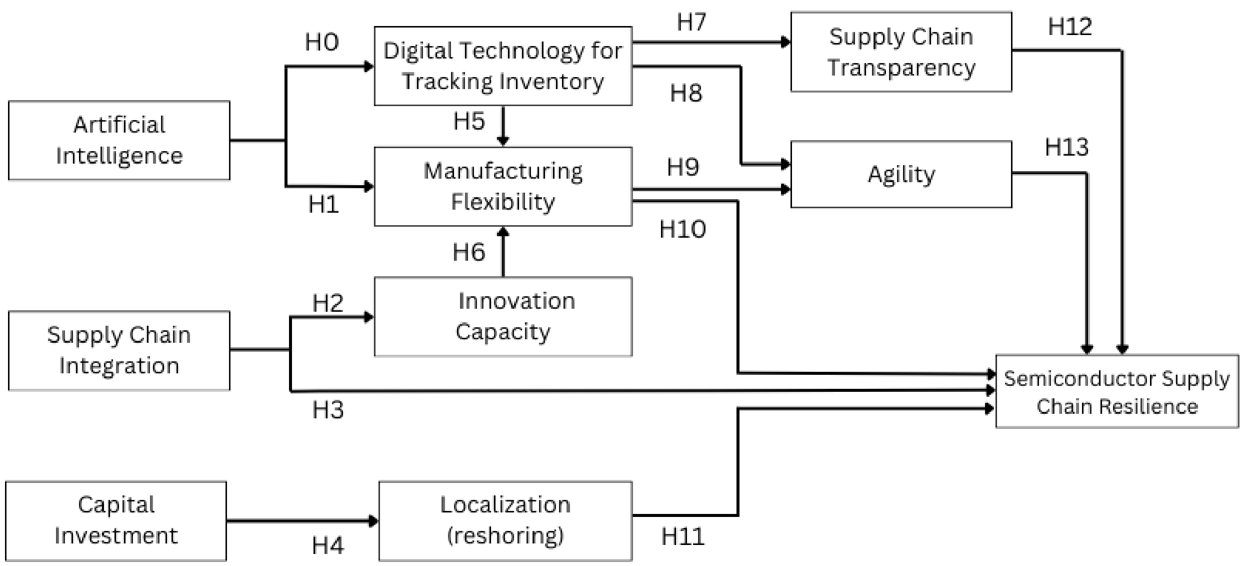

Figure 2. Research framework

4.1 Artificial Intelligence and Digital Technology for Inventory Tracking

Digital inventory tracking technologies enhance supply chain flexibility. Real-time monitoring through advanced technologies such as RFID and IoT, along with AI, allows for swift adaptation to demand fluctuations, optimizing operational efficiency (Ivanov et al., 2019). This connection within the literature leads us to propose H0.

Hypothesis H0: AI is positively related to digital technology for tracking inventory.

4.2 Artificial Intelligence and Manufacturing Flexibility

AI plays a pivotal role in enhancing manufacturing flexibility. By facilitating real-time data analysis and automating complex tasks, AI enables firms to adapt swiftly to evolving manufacturing methods and market demands. This agility reduces downtime and anticipates maintenance needs, thereby improving responsiveness in a rapidly changing technological landscape (Lee et al., 2015; Monostori, 2014). Based on this finding, we propose H1.

Hypothesis H1: AI is positively related to manufacturing flexibility.

4.3 Supply Chain Integration and Innovation Capacity

Supply chain integration positively influences innovation capacity, enabling firms to develop new products and enhance competitiveness. This collaboration is vital for efficient overall supply chain performance (Bertello et al., 2022; Brem et al., 2021). Hence, this leads us to propose H2.

Hypothesis H2: Supply chain integration is positively related to innovation capacity.

4.4 Supply Chain Integration and Semiconductor Supply Chain Resilience (SSCR)

Effective supply chain integration fosters resilience and enhances overall performance in technology-driven sectors. Collaboration and integration across supply chain stages are crucial for adaptability and responsiveness (Massiera, 2024), leading us to propose H3.

Hypothesis H3: Supply chain integration is positively related to SSCR.

4.5 Capital Investment and Localization (Reshoring)

Capital investment is critical for successful reshoring efforts, enabling the establishment of advanced manufacturing capabilities. The initial costs are offset by reduced risks and improved supply chain clarity (Pennacchio, 2023). Hence, we propose H4.

Hypothesis H4: Capital investment is positively related to localization (reshoring).

4.6 Digital Technology for Tracking Inventory and Manufacturing Flexibility

Digital tracking systems enable real-time visibility and facilitate process adjustments, thus enhancing manufacturing flexibility. This adaptability is vital for meeting customer needs in a rapidly evolving market (J. Lee et al., 2015). This leads us to propose H5.

Hypothesis H5: Digital technology for tracking inventory is positively related to manufacturing flexibility.

4.7 Innovation Capacity and Manufacturing Flexibility

Innovation capacity is instrumental in enhancing manufacturing flexibility, allowing firms to adapt processes swiftly. Studies highlight the interplay between innovation and flexibility, emphasizing its impact on business performance (Brem et al., 2021). Hence, we propose H6.

Hypothesis H6: Innovation capacity is positively related to manufacturing flexibility.

4.8 Digital Technology for Tracking Inventory and Supply Chain Transparency

Digital technologies, including blockchain and IoT, significantly enhance supply chain transparency by ensuring efficient data communication and reducing operational costs (Ivanov et al., 2019). This co-dependency leads us to propose H7.

Hypothesis H7: Digital technology for tracking inventory is positively related to supply chain transparency.

4.9 Digital Technology for Tracking Inventory and Agility

Digital technologies improve supply chain agility by enabling real-time inventory insights, which is essential for the volatile semiconductor sector. They facilitate quick decision-making and efficient resource allocation, enhancing responsiveness (Sanders, 2016). This connection leads us to propose H8.

Hypothesis H8: Digital technology for tracking inventory is positively related to agility.

4.10 Manufacturing Flexibility and Agility

Manufacturing flexibility is essential for fostering agility within semiconductor supply chains. Literature underscores the importance of supplier-manufacturer flexibility, supply chain flexibility, and cloud manufacturing (CMfg) in enhancing operational agility (N. C. A. Lee et al., 2020; Mohd Jamal et al., 2019; Veselovská, 2020). Integration of information systems and supply chain collaboration further fortifies this relationship, enabling firms to adapt to market fluctuations efficiently, leading us to propose H9.

Hypothesis H9: Manufacturing flexibility is positively related to agility.

4.11 Manufacturing Flexibility and Semiconductor Supply Chain Resilience (SSCR)

Incorporating manufacturing flexibility into supply chains improves resilience, particularly in high-risk environments (Fu et al., 2023). Enhanced flexibility equips firms to better manage disruptions, as evidenced during the COVID-19 pandemic (Solis et al., 2023). These findings lead us to propose H10.

Hypothesis H10: Manufacturing flexibility is positively related to SSCR.

4.12 Localization (Reshoring) and Semiconductor Supply Chain Resilience (SSCR)
Reshoring enhances supply chain resilience (SSCR) by relocating production domestically, thus mitigating vulnerabilities exposed during semiconductor shortages (Choudhary et al., 2023). Ongoing discussions emphasize the balance between local sourcing and global benefits, highlighting investments in talent and sustainable practices (Grossman et al., 2021). This leads us to propose H11.

Hypothesis H11: Localization (reshoring) is positively related to SSCR.

4.13 Supply Chain Transparency and Semiconductor Supply Chain Resilience (SSCR)
Supply chain transparency, bolstered by technologies like blockchain, enhances resilience by improving risk management and operational efficiency. This transparency is increasingly vital during global disruptions (Kaushik & Jain, 2023), leading us to propose H12.

Hypothesis H12: Supply chain transparency is positively related to SSCR.

4.14 Agility and Supply Chain Resilience (SSCR)
Agility is critical for maintaining SSCR, allowing firms to respond rapidly to shocks and demand fluctuations (Nilesh R. Mate, 2022; Smith, 2023). Factors such as supplier collaboration and digitalization further enhance this resilience (Calvo et al., 2020; Fu et al., 2023), leading us to propose H13.

Hypothesis H13: Agility is positively related to SSCR.

5. Data Collection
Survey questions were developed based on the factors and hypotheses outlined in the previous section. The survey data was generated using dummy responses derived from secondary sources in the literature. To ensure that the generated data closely mirrored real-world patterns, we first conducted a thorough review of relevant studies, extracting key statistical insights and trends. These insights were then used to populate 200 complete surveys through the application of AI and prompt engineering techniques.

By leveraging AI, we were able to create realistic response distributions that align with established findings in the literature while maintaining variability and authenticity in the dataset. This approach not only ensured a structured and systematic data generation process but also enhanced the reliability of the simulated responses. The target of 200 responses was chosen in accordance with recommendations from Hair Jr et al. (2019) for Structural Equation Modeling (SEM), ensuring sufficient statistical power and representation of multiple indicators per factor. Additionally, Kline (2016) suggests that each SEM construct should have at least 10 cases per indicator, further supporting the adequacy of our sample size while accounting for potential non-responses and missing data.

This methodological approach demonstrates the practical application of the developed framework, validating its utility in a structured and data-driven manner.

6. Results and Discussion
This section presents the PLS estimates from the structural model developed in this study, evaluating its performance based on the survey results produced using secondary data.

6.1 Numerical Results
R-squared (R^2) Values
R-squared measures the proportion of variance in the dependent variable explained by the independent variables. A higher R^2 indicates greater predictive power. The R^2 values for this study are indicated in Table 1 below:

Table 1. R-squared values of the factors

Construct	R-squared
Digital Technology for Inventory Tracking	0.447
Manufacturing Flexibility	0.713
Innovation Capacity	0.330
Localization (Reshoring)	0.213
Supply Chain Transparency	0.539
Agility	0.402
Semiconductor Supply Chain Resilience	0.367

The graph in Figure 3 below compares the R-squared values of the seven dependent variables. Amongst all the factors, manufacturing flexibility demonstrated the highest predictive power, while localization showed the lowest.

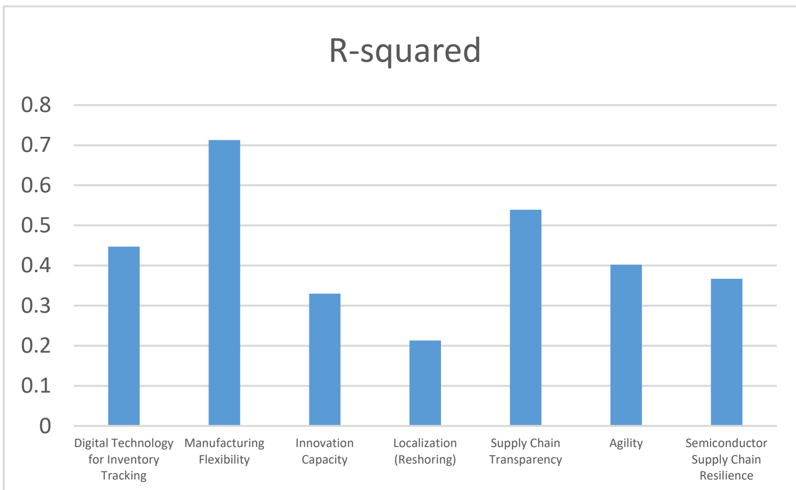

Figure 3. Comparison of the R-squared values

F-squared

In PLS-SEM, F-squared measures the variance in a dependent construct explained by an independent construct, controlling for other variables. Cohen et al. (1990) categorize F-squared values as follows: 0.02 (small effect), 0.15 (medium effect), and 0.35 (large effect). These thresholds are used to assess the impact of each hypothesis. The F-squared values indicate that hypotheses H6, H9, H11, H12, and H13 show no significant effect, while hypotheses H0, H1, H2, and H7 exhibit a large effect. This is indicated in Table 2 below.

Table 2. F-squared values of the factors

Hypotheses	Constructs	F-squared	Degree of Effect
H0	AI and DTTI	0.807	Large Effect
H1	AI and MF	0.441	Large Effect
H2	SCI and IC	0.493	Large Effect
H3	SCI and SSCR	0.275	Medium Effect
H4	CI and LR	0.270	Medium Effect

H5	DTTI and MF	0.341	Medium Effect
H6	IC and MF	0.001	No Effect
H7	DTTI and SCT	1.171	Large Effect
H8	DTTI and AG	0.277	Medium Effect
H9	MF and AG	0.000	No Effect
H10	MF and SSCR	0.068	Little Effect
H11	LR and SSCR	0.005	No Effect
H12	SCT and SSCR	0.006	No Effect
H13	AG and SSCR	0.017	No Effect

Path Coefficients

Path coefficients represent the relationships between variables in the structural model, standardized for comparison. Bootstrapping analysis via SmartPLS revealed that five constructs are insignificant, while the rest are significant at the 99% level. This aligns with the F-squared results, confirming no significant effect for the same factors. Following Chin (1998), path coefficients require t-values above 1.282 for a 90% significance level, 1.645 for 95%, and 2 for 99%. A summary of these results is provided in Table 3 below.

Table 3. A summary of the path coefficient tests

Hypotheses	**Constructs**	**Actual Effect**	**Path Coefficient**	**Standard deviation**	**Observed T-statistics**	**Significance Level**
H0	AI and DTTI	+	0.668	0.069	9.620	99%
H1	AI and MF	+	0.482	0.078	6.211	99%
H2	SCI and IC	+	0.575	0.068	8.504	99%
H3	SCI and SSCR	+	0.447	0.073	6.117	99%
H4	CI and LR	+	0.461	0.069	6.638	99%
H5	DTTI and MF	+	0.450	0.076	5.921	99%
H6	IC and MF	-	-0.015	0.065	0.230	Not Significant
H7	DTTI and SCT	+	0.734	0.056	13.098	99%
H8	DTTI and AG	+	0.631	0.126	5.026	99%
H9	MF and AG	+	0.004	0.128	0.028	Not Significant
H10	MF and SSCR	+	0.272	0.121	2.242	99%
H11	LR and SSCR	+	0.054	0.088	0.606	Not Significant
H12	SCT and SSCR	-	-0.086	0.132	0.655	Not Significant
H13	AG and SSCR	+	0.127	0.108	1.176	Not Significant

6.2 Graphical Results

An overview of these structural model results (showing the path coefficients mentioned in Table 3 above) is shown in Figure 4 below.

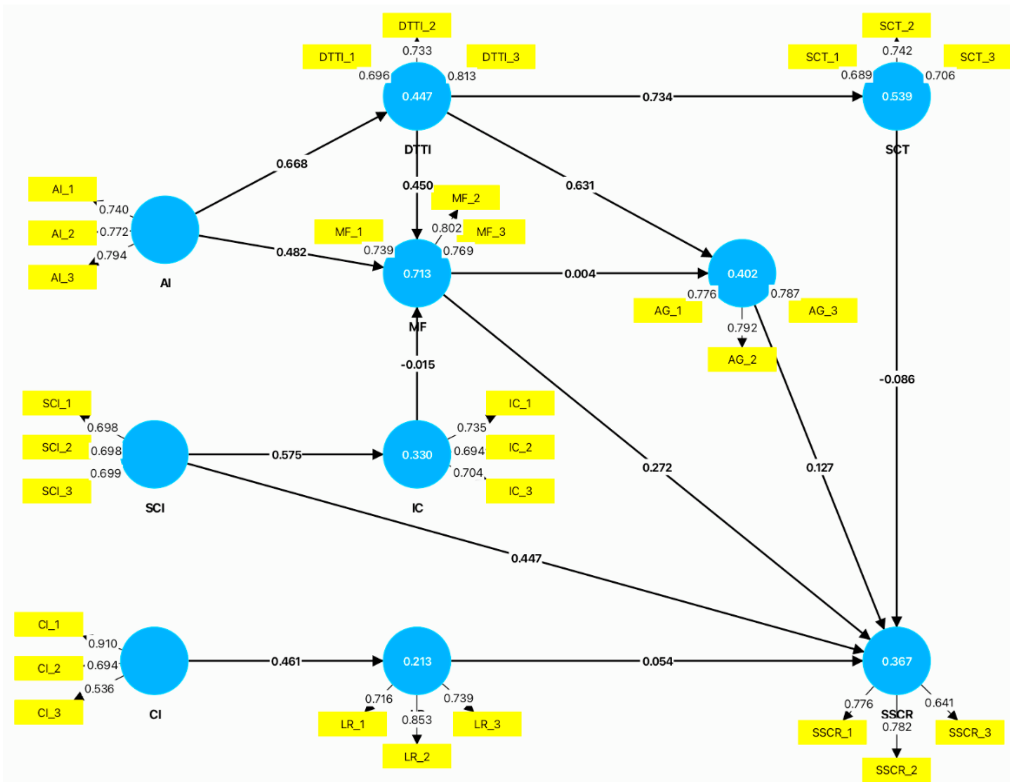

Figure 4. Structural model results

Based on the results from the three previous tables that evaluate the model's performance with the provided data, we determined the effect of the statistics on the effectiveness of the hypotheses. Table 4 below shows which hypotheses were accepted and which ones were rejected (based on the path coefficient, T-statistics, significance level, F-square, and R-square values).

Table 4. Summary of hypothesis results based on the structural equation model

Constructs	**Hypothesis**	**Result**
AI and Digital Technology for Inventory Tracking	H0: AI is positively related to Digital Technology for Tracking Inventory.	Accept
AI and Manufacturing Flexibility	H1: AI is positively related to manufacturing flexibility	Accept
Supply Chain Integration and Innovation Capacity	H2: Supply chain integration is positively related to innovation capacity	Accept
Supply Chain Integration and SSCR	H3: Supply chain integration is positively related to semiconductor supply chain resilience (SSCR)	Accept
Capital investment and Localization (Reshoring)	H4: Capital investment is positively related to Localization (Reshoring)	Accept
Digital Technology for Tracking Inventory and Manufacturing Flexibility	H5: Digital technology for tracking inventory is positively related to manufacturing flexibility.	Accept
Innovation Capacity and Manufacturing Flexibility	H6: Innovation capacity is positively related to manufacturing flexibility	Reject

Digital Technology for Tracking Inventory and Supply Chain Transparency	H7: Digital technology for tracking inventory is positively related to supply chain transparency	Accept
Digital Technology for Tracking Inventory and Agility	H8: Digital technology for tracking inventory is positively related to Agility	Accept
Manufacturing Flexibility and Agility	H1: Manufacturing flexibility is positively related to agility	Reject
Manufacturing Flexibility and SSCR	H9: Manufacturing flexibility is positively related to semiconductor supply chain resilience (SSCR)	Accept
Localization (Reshoring) and SSCR	H10: Localization (reshoring) is positively related to semiconductor supply chain resilience (SSCR)	Reject
Supply Chain Transparency and SSCR	H9: Supply chain transparency is positively related to semiconductor supply chain resilience (SSCR)	Reject
Agility and SSCR	H3: Agility is positively related to semiconductor supply chain resilience (SSCR)	Reject

6.3 Proposed Improvements Based on the Secondary Data
Although the primary aim of this study is to develop the framework for enhancing semiconductor supply chain resilience and test it using secondary data derived from the literature, the results revealed some intriguing insights that suggest potential areas for improvement based on the input data, as outlined below.

Firstly, leveraging advanced technologies and innovation is essential. Implementing AI and digital tracking systems across the supply chain significantly improves visibility, flexibility, and responsiveness. These technologies enable companies to anticipate disruptions and address them more effectively, ensuring smoother operations during periods of uncertainty.

Secondly, enhancing manufacturing flexibility is crucial for adapting to fluctuating demands and integrating new technologies. Investments in versatile manufacturing processes and equipment allow companies to maintain continuous production, even when faced with supply chain challenges. This flexibility is essential in ensuring the industry can pivot rapidly in response to external pressures.

Furthermore, strengthening supply chain integration is vital. Building strong relationships and communication channels within the supply chain fosters a collaborative environment. This enables quicker resolution of issues, improved transparency, and the ability to leverage collective innovation to enhance overall resilience.

Lastly, continuous investment in capital and innovation is necessary to sustain long-term resilience. The research underscores the importance of ongoing financial investments in new technologies and infrastructure, which are crucial for maintaining competitiveness and adapting to emerging challenges in the semiconductor industry.

By focusing on these strategic improvements, semiconductor companies can build more resilient supply chains that are better equipped to handle current and future disruptions.

6.4 Validation
As mentioned in previous sections, this paper presents the development of hypotheses and their relationships within a Structural Equation Modeling (SEM) framework, tested using secondary data drawn from the literature. To further validate the results obtained in this study, the developed survey should be completed by at least 200 respondents who are somehow either affected by or involved in the supply chain chip shortage. The collected primary data should then go through the same calculations and analysis conducted in this paper to compare the findings with this preliminary test.

7. Conclusion
This study builds upon the existing literature on the global semiconductor chip shortage by proposing a framework to analyze key strategies that strengthen semiconductor supply chain resilience. It advocates using Structural Equation

Modeling (PLS-SEM) for this analysis. The framework is developed based on evidence from the literature and expert opinion.

The paper also conducts a preliminary test of the proposed model using artificial survey responses grounded in insights from the literature and expert opinions. This initial test suggests that advanced technologies, such as Artificial Intelligence (AI) and digital inventory systems, play a crucial role in creating agile and transparent supply chains. These technologies are central to enhancing manufacturing flexibility and the industry's ability to swiftly adapt to disruptions. The findings further underscore the importance of integrating supply chain processes, which fosters collaboration and innovation, ensuring long-term competitiveness. Continuous investment in capital and innovation remains vital for growth and for addressing emerging challenges. Manufacturing flexibility emerged as a key enabler of supply chain resilience, allowing for rapid adaptation to external pressures.

Nevertheless, these preliminary results need to be validated by replicating the analysis using real survey responses, as opposed to the artificial data employed in this study. This represents a promising avenue for future research with significant potential for further contributions to the field.

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Prof. Dr. Laoucine Kerbache is full Professor of Logistics and Supply Chain Management and a founding member of the Engineering Management and Decisions Science (EMDS) Division within the College of Sciences and Engineering (CSE, HBKU) since 2018. In addition, over the last 35 years, Dr. Kerbache has been in academia (teaching and research) with 24 years at HEC Paris where he was full Professor of Operations management, Logistics, and Supply Chain Management. While at HEC Paris, he held various academic and managerial positions including Associate Dean in charge of the HEC Paris PhD Program (during 5 years), Dean and CEO of HEC Paris in Qatar, in addition to other academic positions. He holds a Ph.D., an MSc. and a BSc. degrees in Industrial Engineering and Operations Research from the University of Massachusetts at Amherst (USA). His research areas span interfaces of industrial engineering, operations research, operations management, logistics and supply chain management with a special focus on modelling and optimization of problems relative to industrial facilities and service organizations. He is active member of numerous professional organizations such as INFORMS, POMS, EUROMA, IEOM, etc.