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Review

A Strategic Recovery Framework for Semiconductor Supply Chains

Tushar Verma [1], Gunjan Soni [1] and Balkrishna Eknath Narkhede [2,*]

[1] Malaviya National Institute of Technology Jaipur, Rajasthan 302017, India
[2] Department of Operations and Supply Chain Management, Indian Institute of Management Mumbai, Mumbai 400087, India
* Correspondence: benarkhede@iimmumbai.ac.in

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Abstract: Semiconductor manufacturing has become a strategically critical global industry, yet its supply chains remain exposed to persistent disruption from geopolitical conflict, natural disasters, cyberattacks, and intellectual property risk. The objectives of the current research project are to review available literature on semiconductor supply chain recovery and resilience, recognize gaps in research on recovery from disruption, and to propose a structure to allow for developing recovery strategies, this study conducts a systematic literature review (SLR) following the PRISMA methodology, drawing on a final dataset of 344 publications from the Scopus database and synthesizing results through bibliometric network visualization using VOS viewer. The findings reveal a substantial imbalance in the literature: while resilience strategies for absorbing and mitigating disruptions are extensively studied, structured approaches for post-disruption recovery and restoration of long-term operational readiness remain limited. Building on this finding, the paper proposes a Semiconductor Supply Chain Recovery Framework that treats resilience and recovery as distinct but interdependent imperatives. The framework organizes recovery strategies across four sequential response horizons detection, Immediate, Short-Term, and Long-Term and three parallel tracks Operational, Collaborative, and regulatory spanning early disruption detection, cross enterprise coordination, and phased, node-by-node restoration of production and distribution capacity. To operationalize these strategies across differing organizational contexts, the study further develops a Recovery Strategy Applicability Matrix that maps recovery actions onto four firm archetypes according to their resource and institutional capacity. Given the fragmented, proprietary, and globally distributed nature of semiconductor manufacturing, and the compounding effects of geopolitical tension and cyber threats on both resilience and recovery speed, this framework connects passive risk identification to proactive recovery engineering for the global semiconductor supply chain.

Keywords: semiconductor supply chain; supply chain resilience; supply chain recovery; biblio-metric analysis; recovery framework; geopolitical risk; systematic literature review; VOS viewer

1. Introduction

Semiconductors are regarded as one of the principal technological resources of current times in the twenty-first century's industrial context [1]. They form the base technology upon which industries such as telecommunications, automotive, healthcare, consumer electronics, aerospace, artificial intelligence, and defense systems depend to operate [2]. The increasing global adoption of digital technologies—including cloud computing,



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IoT devices, and advanced automation has further deepened the world's structural dependence on semiconductor supply chains [3]. As this dependence has increased, the structure and organization of semiconductor supply chains have also evolved, creating new sources of efficiency as well as new forms of systemic vulnerability.

This transformation has been driven by the increasing specialization and fragmentation of semiconductor manufacturing over the past several decades. The traditional model of a fully integrated device manufacturer (IDM), in which a single company performs activities ranging from chip design and fabrication to testing and packaging, has increasingly evolved toward a more fragmented ecosystem involving fabless design firms, foundries, outsourced semiconductor assembly and test providers, and specialized suppliers, mainly located in East Asia, that outsource their production to each other. This specialization has also resulted in significant geographic concentration of semiconductor manufacturing and critical upstream capabilities, particularly across East and Southeast Asia. Such concentration allows firms to benefit from economies of scale and specialized capabilities, but it also increases dependence on a limited number of manufacturing locations and supply-chain nodes [4]. However, while this fragmentation and specialization have provided advantages in terms of scale and operational efficiency, they have also created extensive interdependencies among raw-material suppliers, equipment manufacturers, foundries, assembly and testing providers, transportation networks, and downstream customers [5]. As a result, the efficiency gained through specialization has also increased the complexity and interconnectedness of the global semiconductor ecosystem, making it increasingly susceptible to external disruptions.

The vulnerability created by these structural interdependencies became particularly evident during the COVID-19 pandemic. Restrictions on movement, temporary factory closures, logistics disruptions, and sudden changes in demand contributed to severe imbalances between semiconductor supply and demand. The resulting chip shortages forced several automotive manufacturers to reduce or temporarily halt production, generating substantial economic losses across the automotive sector [6]. Beyond the COVID-19 pandemic, the semiconductor supply chain has also been exposed to a broader range of disruptions, including geopolitical conflicts, natural disasters, cyberattacks, export controls, and strategic competition between the United States and China, particularly in relation to Taiwan [7–9]. The concentration of advanced semiconductor fabrication facilities in regions exposed to seismic activity, water stress, and other environmental risks further increases the potential for localized disruptions to propagate across the global supply chain [10]. These recurring disruptions have therefore shifted the focus of researchers and practitioners from merely identifying supply-chain vulnerabilities toward developing capabilities that can maintain continuity and reduce the impact of disruptions under highly uncertain conditions.

In response to these threats, organizations and policymakers have taken substantial steps to create resilience in their supply chains in response to these ever-increasing threats to supply chain continuity. Examples of these steps include investing in anticipatory buffers, diversifying supplier bases, and implementing real-time monitoring systems to absorb foreseeable shocks to their supply chains [11]. However, resilience has finite limits. While resilience enables a supply chain to anticipate, absorb, adapt to, and withstand disruption, it does not necessarily provide a structured pathway for restoring operations when the magnitude of a disruption exceeds the system's capacity to absorb the shock [12]. Once these resilience capacities are exceeded and operational continuity is no longer sustainable, the central managerial challenge shifts from absorbing the disruption to restoring material flows, productive capacity, and supply-chain functionality. Thus, it is at this point that recovery becomes the key operational imperative. Recovery can therefore be understood as the systematic process of restoring material flows, productive capability, and strategic position following a disruption [13,14]. From a managerial perspective, resilience and recovery represent distinct capabilities and therefore require different forms of investment, decision-making, and governance [15].

This distinction becomes particularly important in the semiconductor industry, where structural and technological characteristics make post-disruption recovery considerably more difficult than in many other industrial sectors. The construction of semiconductor fabrication plants requires tens of billions of dollars in capital investment and typically involves lead times of several years, making rapid restoration of lost production capacity extremely difficult [16]. Recovery is further constrained by the highly specialized equipment used in semiconductor fabrication, lengthy equipment procurement and installation cycles, stringent process qualification requirements, and the availability of highly skilled technical personnel. These characteristics mean that production cannot simply be transferred to an alternative facility without significant technical validation, coordination, and time. Moreover, the geographic concentration of advanced manufacturing capacity limits the availability of immediately deployable alternative production sites, particularly for technologically advanced and highly specialized products [17]. Geopolitical constraints on partner networks, export controls, and competitive stockpiling observed during the 2020–2022 chip shortages further restrict firms' ability to identify and activate alternative sources during recovery [18,19]. Digital tools such as AI-enabled demand sensing, blockchain-enabled provenance tracking, and simulation-based scenario planning have the potential to support faster and more reliable

recovery; however, their adoption remains inconsistent across the semiconductor value chain [20,21]. Taken together, these characteristics indicate that strengthening recovery capabilities in the semiconductor industry requires not only technological innovation but also a systematic understanding of recovery strategies across different stages and actors of the semiconductor ecosystem.

Despite the growing importance of recovery, the semiconductor supply-chain literature remains considerably more focused on resilience, risk mitigation, disruption preparedness, and continuity than on structured post-disruption recovery [1]. Existing studies provide valuable insights into how supply chains can anticipate and absorb disruptions, but comparatively less attention has been given to how semiconductor firms can systematically restore production, material flows, supplier relationships, and operational capability once resilience capacities have been exceeded. This gap is particularly important because recovery decisions in the semiconductor industry involve multiple time horizons, organizational capabilities, and stakeholders, while the effectiveness of a given recovery strategy may vary considerably across firms and supply-chain positions. Accordingly, there is a need for an integrated framework that moves beyond the identification of vulnerabilities and resilience mechanisms to provide a structured view of post-disruption recovery strategies within the semiconductor supply chain.

Against this backdrop, this study investigates the post-disruption recovery of global semiconductor supply chains and examines how recovery capabilities can be systematically developed when resilience-based measures are insufficient to restore operational continuity. To address this objective, a systematic literature review (SLR) was conducted using a corpus of 344 publications related to semiconductor supply-chain resilience, disruption, and recovery. The literature was examined using bibliometric analysis and VOS viewer to identify major research themes, keyword relationships, and emerging areas of research within the field. The findings from the literature analysis were subsequently used to develop a Semiconductor Supply Chain Recovery Framework (SSCRF), which organizes recovery strategies across different recovery horizons and operational, collaborative, and regulatory tracks. In addition, a Recovery Strategy Applicability Matrix is developed to distinguish the applicability of recovery strategies according to the capabilities and characteristics of different firms within the semiconductor ecosystem. This approach recognizes that recovery strategies are not uniformly applicable across firms and that factors such as organizational capability, supply-chain position, resource availability, and strategic importance influence recovery decisions. It develops an integrated recovery framework based on bibliometric analysis together with evidence from the semi-conductor shortage of 2020–2022. By doing so, it identifies where recovery capabilities are lacking in the industry and presents interventions at both the firm level and the policy level aimed at reducing recovery time and restoring supply chain viability after resilience-based defenses have been exhausted. The study therefore emphasizes the need for firms and policymakers to consider recovery readiness as a distinct strategic capability rather than treating it solely as an extension of resilience planning. By explicitly addressing the transition from disruption absorption to post-disruption restoration, the study seeks to provide a more structured basis for reducing recovery time and improving the long-term viability of semiconductor supply chains. Consequently, the ability to recover rapidly after a disruption may ultimately become more valuable than the ability to withstand the disruption itself [22,23].

The study contributes to the existing literature in three principal ways. First, it integrates different recovery horizons to provide a structured view of how recovery actions evolve from immediate response to longer-term restoration and strategic rebuilding. Second, it organizes recovery interventions across operational, collaborative, and regulatory tracks, thereby recognizing that recovery extends beyond actions undertaken by individual firms. Third, it differentiates the applicability of recovery strategies according to firm-level capabilities, providing a basis for understanding why the same recovery intervention may not be equally suitable across different semiconductor supply-chain actors. Together, these contributions provide an integrated perspective on semiconductor supply-chain recovery and extend the existing literature beyond resilience-oriented approaches. The remainder of this paper is organized as follows. Section 2 reviews the existing literature on semiconductor supply chains, resilience, and recovery and establishes the research gap. Section 3 presents the systematic literature review methodology, including the PRISMA protocol and bibliometric approach. Section 4 presents the keyword co-occurrence and thematic analysis using VOS viewer. Section 5 develops and presents the Semiconductor Supply Chain Recovery Framework and the Recovery Strategy Applicability Matrix. Section 6 discusses the theoretical and practical implications of the findings and concludes the study.

2. Literature Review

This section reviews the literature on semiconductor supply chains, with particular emphasis on supply chain recovery, the structural characteristics that make recovery challenging in the semiconductor industry, and the research gap motivating the present study.

2.1. Semiconductor Supply Chain

The semiconductor supply chain has turned out to be one of the most strategically important industrial systems due to the significance of semiconductors in various industries such as consumer electronics, automotive, medicine, aerospace, artificial intelligence, and the military [1,2,24]. Unlike the traditional manufacturing sector, the semiconductor supply chain is characterized by a high level of fragmentation, with multiple suppliers of raw materials, machinery, contract manufacturers, assemblers and testing facilities, and systems integrators acting in a global marketplace [4,5]. Nevertheless, the increased specialization may enhance the efficiency of production and promote technological development, the increased level of specialization leads to greater interdependence of companies operating in the semiconductor supply chain, thus making them susceptible to political risks, natural disasters, cyberattacks, export bans, and variations in demand [1,13,25,26].

2.2. Definition of Recovery

In supply chain management, recovery is a combination of actions and strategies to return a supply chain's operations to an operational state prior to a disruption, so that products can be delivered to customers on time and at the lowest cost [27]. The importance of recovery for the semiconductor supply chain (SSC) is significantly amplified by the critical role that chips play across virtually every sector of the economy. The SSC is one type of critical infrastructure that is needed to sup-port the global technology industry, which involves producing and distributing advanced electronic components [13]. Recovery is more than an operational objective; it also serves as a geopolitical and strategic necessity.

Resilience is the capacity to absorb a shock and continue operating. Recovery is the set of actions that restore flows, capacity, and position after that capacity is exceeded. The resilience of the supply chain provides for a timely recovery from disruptions while minimizing their overall impact, returning the supply chain to a normal operational state, maintaining the supply of goods to customers without interruption, and ensuring optimal financial performance of the supply chain [1]. Thus, recovery is located at the intersection of reliability and resilience: resilience is the basis upon which the supply chain can recover from an interruption; reliability is the basis upon which the supply chain can avoid disturbances in the first instance; the integration of both strategies will assist semiconductor companies in managing uncertainty and maintaining a continuous production system despite the occurrence of disruption [7]. This imbalance is quantified in the bibliometric findings presented in Section 4: resilience mechanisms are comparatively well studied, whereas the processes governing restoration once those mechanisms are exhausted remain underexamined. This gap is the contribution this study addresses, with recovery positioned as its central focus [15,28].

Given this distinction, recovery strategies can further be separated by the extent of intervention they require. The recovery strategy can be further classified into those that will require only planning level changes and those that will promote physical change. A recovery strategy that relies on only supply chain planning changes does not require physical modifications to the manufacturing process, is therefore more readily executed, than either producing more units or increasing the speed of production would be in a capital-intensive and complex manufacturing environment like the semi-conductor industry [27]. This distinction is instrumental to help those who study the semiconductor industry understand that recovery timelines in the semiconductor industry are structurally longer than in most other industries. These planning-versus-physical differences in turn justify the phased approach to recovery—immediate, short-term, and long-term—examined in Section 5.1.

2.3. Why Recovery Is Uniquely Hard in Semiconductors

Recovery from the semiconductor supply chain's disruptions will involve recovery challenges that are different in quality from those faced with other conventional industries. The semiconductor supply chain is more complex in comparison to traditional supply chains due to the complexities related to processes, the need to manufacture at greater length due to supply chain length, an extreme reliance on highly specialized inputs, high capital intensity and dependence upon technology, geopolitical factors which affect all components of the supply chain as well as their strategic importance across multiple sectors of the economy [29].

With regards to barriers to recovery, the most significant barrier is found in extreme con-centration of manufacturing capability. Approximately 70–72 percent of total worldwide revenue associated with semiconductor foundries is controlled by TSMC with approximately 90 percent of the 3 nm chips and a similar share of the 5nm chips in the same category (e.g., utilized to provide processing power to AI accelerators, flagship smartphones and high performance computing) being manufactured by TSMC [16]. As such, disruption occurring at a single node can cause tremendous rippling effects through the entire global technology ecosystem. On the equipment side; however, ASML is the sole producer of extreme ultraviolet lithography (EUV) machines (i.e., the

machines that enable leading edge chip manufacturing) due to the unique requirement of producing light with a wavelength of 13.5 nanometers (extreme ultraviolet, part of the electromagnetic spectrum) and as such there has not been a manufacturer other than ASML with EUV lithography capability, therefore the entire industry capability to advance is therefore constrained by the EUV production schedule established by ASML [30].

Due to the capital-intensive nature of the semiconductor industry, the industry at large is constrained in terms of speed in which recovery can occur. Due to their capital intensity, semiconductor manufacturers tend to run their manufacturing plants as close to full capacity as possible so that there is little availability for unexpected spikes in demand. In the past decade, actual utilization of semiconductor manufacturing has consistently remained at or above 80 percent, with a peak of close to 90 percent in 2020, indicating that plants are running at near total capacity [10]. Because of the chronic near-total capacities at which semiconductor plants have operated, they are essentially "out of commission" when there are unexpected spikes in demand and can only realistically respond to demand increases through excess capacity at existing plants or through "reactive adjustments" to production capabilities.

Another significant factor limiting recovery speed is manufacturing lead times for lithography tools and process equipment. Lead times for lithography tools and other types of process equipment remain long and require a long time to add capacity in the semiconductor industry, as these tools are exceptionally complex to manufacture; lead-time challenges are exacerbated by workforce constraints for packaging, testing, and process control roles that require highly specialized skill sets. Due to a shortage of skilled workers, there can be significant delays in ramping up new facilities even when capital investments in the semiconductor industry are strong [3]. There are also significant costs and time-related obstacles associated with construction of semiconductor fabrication facilities and ramping-up production in these facilities, as it typically takes more than a year to build significant additional capacity in existing semiconductor manufacturing facilities (or more than three years to complete construction of a new semiconductor fabrication facility), making it extremely difficult to increase overall semiconductor manufacturing (supply) quickly [6].

In the end, disruptions can recur within one area. Disruptions affecting part of the supply chain can very rapidly ripple through the upstream or downstream supply chain originating in that area and create an even larger overall disruption effect as well as increase overall vulnerability whenever a disruption occurs simultaneously within more than one region or within critical production centers [13]. These structural elements: concentration, capital intensity, long lead times, and propagation, combined to create a recovery environment for supply chains that is unlike any other global industry. Collectively, these structural characteristics distinguish semiconductor supply chains from conventional industries, making recovery significantly slower and more resource-intensive [28,31]. Consequently, recovery strategies must be phased and coordinated rather than reactive. Given these structural constraints, recovery cannot rely on a single intervention; instead, firms require recovery strategies aligned with different stages of disruption. Accordingly, the Section 5 classifies recovery methods according to their implementation horizon.

2.4. Research Gap and Study Objectives

Every sector of the economies of today depend largely on semiconductors like those found in consumer electronics, automotive systems, defense and medical devices. Despite having formed the backbone of many of today's sectors, the academic literature surrounding supply chains for semiconductors and their levels of resilience have been published in a variety of different forms, meaning most studies concerned themselves with only isolated instances of disruption rather than with the complex and interconnected failure patterns that characterize most real world networks [1]. This is further compounded by a lack of standardization in the way resilience outcomes are measured [15], so different industries cannot rely on a common basis to develop coherent and comparable response strategies across their entire sector. While being very important, existing studies have focused almost exclusively on issues around preparedness and mitigation for risk and have not addressed recovery separately from these other issues [28]. Existing frameworks fall short of this integration in specific ways. The conceptual framework proposed in [1] maps resilience capabilities and implementation challenges comprehensively but stops short of specifying a phased recovery sequence or differentiating recovery pathways by firm type. The MARE framework in [27] offers a semantic model for disruption management and resilience evaluation but does not distinguish planning-level recovery actions from those requiring physical or capital investment, nor does it address firm heterogeneity. Broader resilience reviews such as [28,31] and establish theoretical foundations for resilience and viability but treat recovery as a downstream consequence of resilience rather than as a distinct construct requiring its own timeline, metrics, and governance structure. The present study addresses each of these gaps directly through the SSCRF's horizon-based structure and firm-differentiated matrix. This pattern is directly reflected in the biblio-metric findings of Section 3.1, where resilience-related keywords formed the dominant and most densely

connected clusters in the co-occurrence network, while recovery-related terms remained comparatively sparse and peripheral [22].

The recovery period (immediately following the end of the effectiveness of the resilience mechanisms and ending when returning to pre-disruption condition) is not an extension of the resilience mechanism, but is actually a different challenge that will require separate measures for assessment, and separate coordination procedures to support a recovery plan [28]. Upstream weaknesses will add considerable complication to the recovery process. For example, impediments such as reliance on rare earths; geographic concentration of advanced lithographic equipment and geopolitical is-sues may cause cascading failures all through the manufacturing environment before it becomes obvious that there will be some type of failure downstream [31]. Traditional strategies in recovering from downstream failures such as increased inventories will not be sufficient; therefore, proper recovery procedures need to include alternatives to materials, activation of alternative suppliers and reconstruction of production schedules.

Sustainability should be embedded into recovery frameworks as a fundamental element rather than treated merely as an addendum to recovery efforts, due to the fact that energy intensity, tighter environmental regulations, and climate-driven disruptions have resulted in recovery and sustainability commitments being intertwined [32]. If businesses can restore throughput by ignoring the sustainability targets, they could create deeper future structural failures. In addition, no metrics are currently established to measure the effectiveness of recovery, including how timely goods returned to output, supplier reconfiguration, and long-term stability of the network [31]. This absence of recovery-specific measurement leaves both academia and industry without vali-dated tools to guide restoration once resilience capacity has been exceeded, representing a gap with direct consequences for operational continuity across the sector [22]. To fill these gaps, a systematic literature review based on the PRISMA methodology will use Scopus, and bibliometric network visualization analysis to create thematic clusters and establish baseline recovery framework guide-lines for multi-functional supply chain network recovery [1,22]. To the authors' knowledge, no existing study combines bibliometric evidence of the resilience–recovery imbalance with a phased, multi-track recovery framework and a firm-differentiated applicability matrix within a single model. This integration constitutes the central novelty of the present study: rather than treating recovery as a single undifferentiated capability, it disaggregates recovery into sequential response horizons and firm-specific pathways, offering a level of operational and organizational granularity absent from prior semiconductor supply chain research. To address these identified gaps, this study pursues the following research objectives.

(1) Map how the semiconductor supply-chain literature treats resilience versus recovery.
(2) Identify the thematic structure and under-studied nodes via bibliometric co-occurrence.
(3) Propose a phased, multi-track recovery framework differentiated by firm archetype.

3. Research Methodology

This section outlines the systematic review methodology, detailing the protocol adopted, database selection, search strategy, screening process, bibliometric analysis techniques, and publication trend patterns guiding this study's rigorous literature review.

3.1. Systematic Review Protocol

This study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol to ensure a transparent, reproducible, and replicable review process. PRISMA structures the review into four sequential stages—identification, screening, eligibility, and inclusion, each of which is documented to minimize selection bias and support methodological rigor in bibliometric synthesis, consistent with bibliometric-based systematic reviews applied elsewhere in the supply chain resilience literature [11,33].

3.2. Database Selection

The undertaking of this research using Scopus was due to the fact that Scopus focuses on a myriad of peer-reviewed publications in journals, books, and conference proceedings regardless of the type of publication. This database has proved its ability to cover research-related areas in semiconductors supply chains since it can provide credible publications on the topic. Moreover, this database is known to offer bibliographical data in a standardized manner that allows using the data in bibliometric software tools such as VOS viewer and Bibliometric.

3.3. Search Strategy

A structured keyword set was developed to capture literature on supply chain resilience from both a technical and a managerial perspective within the semiconductor ecosystem [11,34], incorporating terms associated with

risk and recovery alongside the core resilience concept [25,35]. The following search string was applied to article titles, abstracts, and keywords:

TITLE-ABS-KEY (“supply chain” OR “logistics”) AND TITLE-ABS-KEY (“semiconductor”) AND TITLE-ABS-KEY (“resilience” OR “risk” OR “recovery”) AND PUBYEAR > 2012

The search was conducted in May 2026 and restricted to articles and conference papers, published in English. This search returned 422 documents, which formed the foundation for formal analysis.

3.4. Screening and Selection

Document types were limited to Articles (ar) and Conference Papers (cp), after which 348 documents remained. Only publications written in the English language were considered for the analysis, and following this filtering step, 344 documents were collected for further screening; no additional records were excluded at this stage, and all 344 were retained. Unrelated items were then screened out to retain only records relevant to the study’s scope. The screening and selection procedure, including records excluded at each stage and the final count retained for analysis, is summarized in the PRISMA flow diagram (Figure 1).

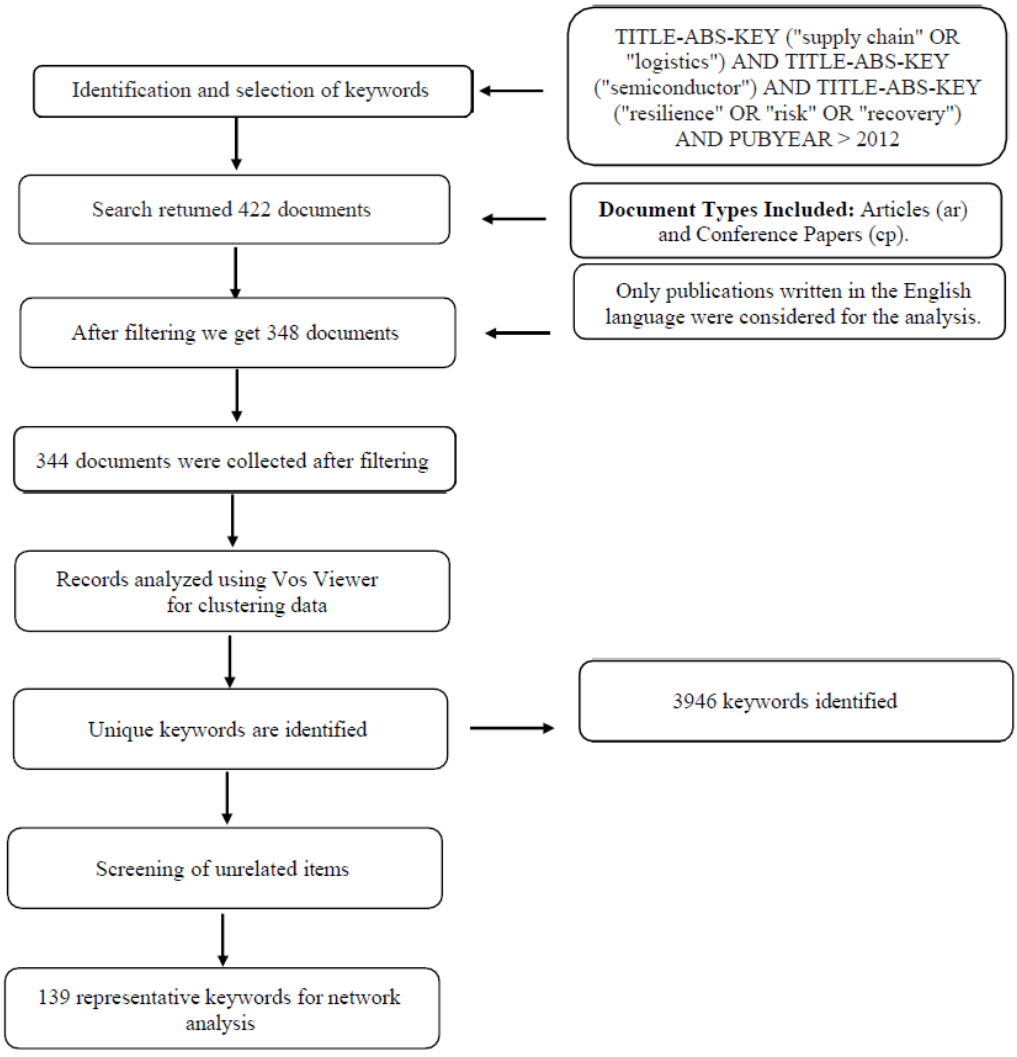


Figure 1. Detailed screening and selection procedure.

3.5. Bibliometric Analysis

Keyword co-occurrence analysis was performed using VOS viewer (version 1.6.20), following the bibliometric approach adopted in comparable supply chain resilience reviews [33]. The analysis initially identified 3946 unique keywords across the retained document set. These were refined to 139 representative keywords for network construction through a keyword cleaning procedure. A minimum occurrence threshold of 5 was applied to retain keywords for the co-occurrence network.

4. Research Theme Identification Using VOS Viewer

4.1. Publication Trends and Thematic Distribution

An examination of yearly global publication trends displays an ongoing changing outlook for academia and industry interest in the semiconductor supply chain's ability to withstand shocks [5,35]. This trend was examined using the search string ABS ("Supply chain" OR "Logistics") AND ABS ("Semiconductor"), which returned 1753 research articles for classification into thematic categories (Figure 2). Within the publication themes identified, "production" (430 articles) tops the list, followed closely by "design" (411), then followed by "management" (335). The centralization of published papers around these three themes indicates a significant researcher effort in providing assurance and stability to the semiconductor supply chain's operational continuum [5]. Aside from the area of production, "Risk" has been identified as a major area of research with 251 articles published, showing the importance and urgency both in academia and industry for identifying risks related to geopolitical risks, cyber risks, intellectual property theft, natural disasters, and changing demand patterns [25]. The resilience association category has 133 articles published and reflects an increasing awareness of the need for adaptive recovery mechanisms and operational flexibility within semiconductor manufacturing supply chains [1].

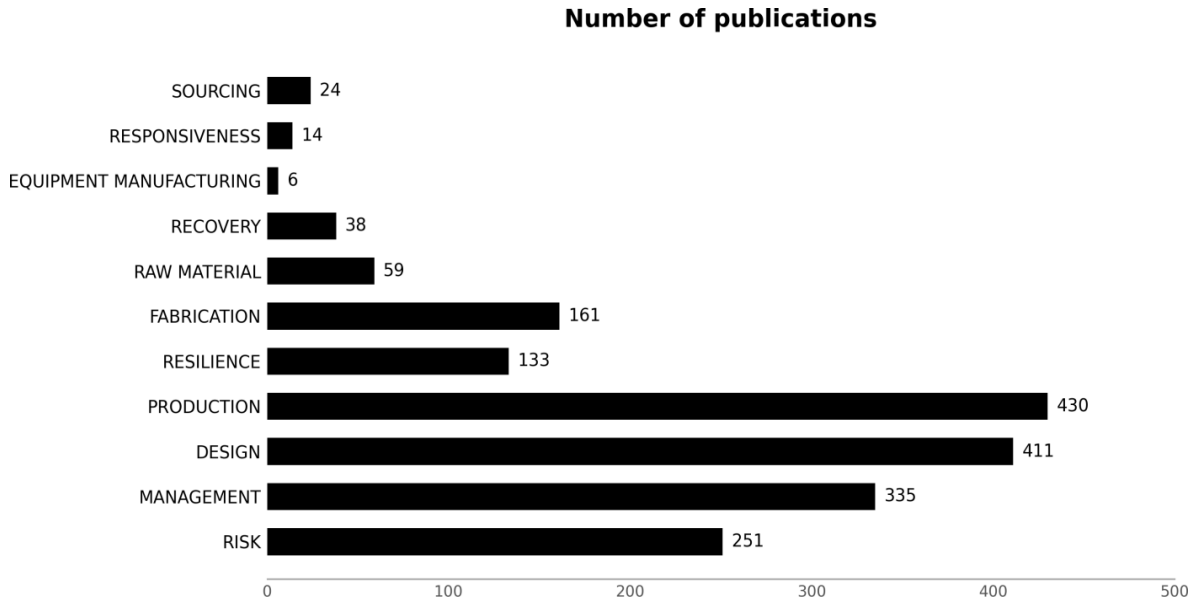


Figure 2. Publication trends.

Representing number of publications by researched topics on the other hand, upstream processes have been studied less: fabrication has had 161 articles published, raw material supply has had only 59 articles published, and equipment manufacturing has only had 6 articles published. These significant differences highlight a major strategic blind spot. Recovery related articles total 38, while the number of articles focused on responsiveness is only 14, demonstrating an extremely skewed relationship between pre-emptive risk management and reactive/adaptive strategies. It is worth noting that several articles span more than one thematic category, which is why the sum of articles across these themes exceeds the total of 1753 retrieved through the search string. Although publication trends demonstrate increasing scholarly attention to semiconductor supply chain resilience, they do not explain the conceptual focus of the literature or how its constituent themes relate to one another.

To complement the temporal analysis of publication trends, keyword co-occurrence analysis was conducted to identify the conceptual structure of semiconductor supply chain recovery research, consistent with established systematic review practice [15,28]. Reviewing the extant literature, it is apparent that several pieces of research have investigated analytical frameworks for resilience capability analysis using temporal dimensions looking at the timeline for developing and demonstrating resilience capabilities before disruption—yet these efforts have been somewhat disparate and not yet consolidated into a model that can be applied to semiconductor supply chains during disruption and after disruption [13]. The framework includes four layers of classification (supply chain stage, functional group, motivators, and focus problem), all of which correlate with the four phases of an entity's operational activities within the semiconductor production ecosystem from design and raw material procurement, through fabrication, to final commercial integration [1]. Most of the literature focuses on developing prevention and preparedness plans for manufacturing disruptions [23]. In contrast, only a small percentage of the existing academic literature examined the recovery aspect of semiconductor manufacturing disruptions. This imbalance

may have considerable ramifications for the semiconductor industry because restoring a semiconductor manufacturer to a state of operation following a manufacturing disruption generally takes a long time due to the length of production lead times, the significant amount of specialized equipment and facilities typically needed to fabricate semiconductors, and the large capital investments that companies must make in order to develop and maintain their manufacturing infrastructure [13].

In addition to the recovery gap, the reviewed literature indicates a dominant focus on processes throughout the manufacturing life cycle, while relatively few studies address upstream dependencies between semiconductor manufacturers and suppliers of materials, such as rare earths, and specialized equipment, including precision tools and machines [5], highlighting a critical gap given manufacturer's reliance on these inputs within an ever-changing global supply chain. Four main drivers continue to define and shape resilience-based research: semiconductor shortages, theft of intellectual property, rapid evolution of technology, and fluctuating customer demand [25]. Based upon the empirical research landscape across studies reviewed, a commonality of method applied to study resilience in semiconductor supply chains exists. Researchers have employed various methodologies such as quantitative methods (e.g., machine learning, predictive analytics, optimization modelling, neural networks, and statistical forecasting) extensively. Qualitative methods (e.g., expert interviews, organizational assessments, and case studies) have provided additional depth to understanding how organizations make decisions related to developing a resilient operational plan in real-world industrial applications.

4.2. Cluster Analysis by VOS Viewer

Bibliometric cluster analysis was performed using the VOS viewer software environment to develop a mapping of how the key research themes in the literature pertaining to semiconductor supply chain resilience relate to each other [20,33]. This approach involved analyzing the co-occurrence frequency of keywords found in published academic works to identify both conceptual relationships and dominant thematic clusters within an overarching body of research. The original dataset contained 3946 total unique keywords; however, systematic refinement was applied including the discard of non-relevant words and combining words with similar meanings (e.g., "IoT" and "Internet of Things Technology") which resulted in the establishment of 139 representative keywords, thus creating a strong basis for conducting network analysis [1].

Through the use of this refined list of keywords, VOS viewer was able to create a visual co-occurrence network that illustrates how core concepts are related to each other in the literature related to semiconductor supply chain resilience. Each keyword in the co-occurrence network is represented by a node in the visualization, while the lines that connect the nodes (edges) differ in width depending on how often the keywords are found together in the literature reviewed—a common method in bibliometrics for visualizing topical proximity and conceptual clustering within a domain of research.

There are five main clusters of connection found within the overall network (Figure 3): (1) Hardware Security and Integrated Circuit Design; (2) Semiconductor Industry, Risk Assessment and Supply Chain Management; (3) Supply Chain Operations and Resilience; (4) Semiconductor Materials, Packaging and Circular Economy; and (5) a smaller cluster comprising bibliometric and clinical-study related terms that fall outside the core research focus. In general, terms related to hardware security and integrated circuit design are concentrated in the upper portion of the network, terms related to supply chain operations and resilience are concentrated in the lower-left portion, and terms related to the semiconductor industry, risk assessment, and supply chain management occupy the central and right-hand portion, indicating continued attention by researchers on ensuring production continuity, safeguarding hardware integrity, and avoiding disruptions to operations [35]. Overall, the keyword network indicates that resilience remains the dominant research focus, while recovery-oriented strategies are comparatively underexplored [2,22]. This observation forms the basis for the development of the proposed recovery framework.

The focus of this study is to investigate a gap in existing literature regarding semiconductor supply chain recovery by placing an emphasis on recovery strategies. Unlike prior work that treats recovery strategies as a uniform set of actions applicable across firms, this study's contribution is a constraint-based recovery framework that explicitly accounts for firm-level differences in budget, available time, and organizational scale. This is, to the authors' knowledge, the first attempt to formally pair recovery time horizons with firm capability archetypes in the semiconductor context, producing a structured, non-uniform recovery pathway that differs by organization type—for example, a small startup versus a large OEM or government-backed manufacturer. This new approach to recovery directly relates to the ongoing issues identified in the literature and helps provide both practitioners and researchers with a model to guide their efforts in recovering the semiconductor supply chain after it has been disrupted.

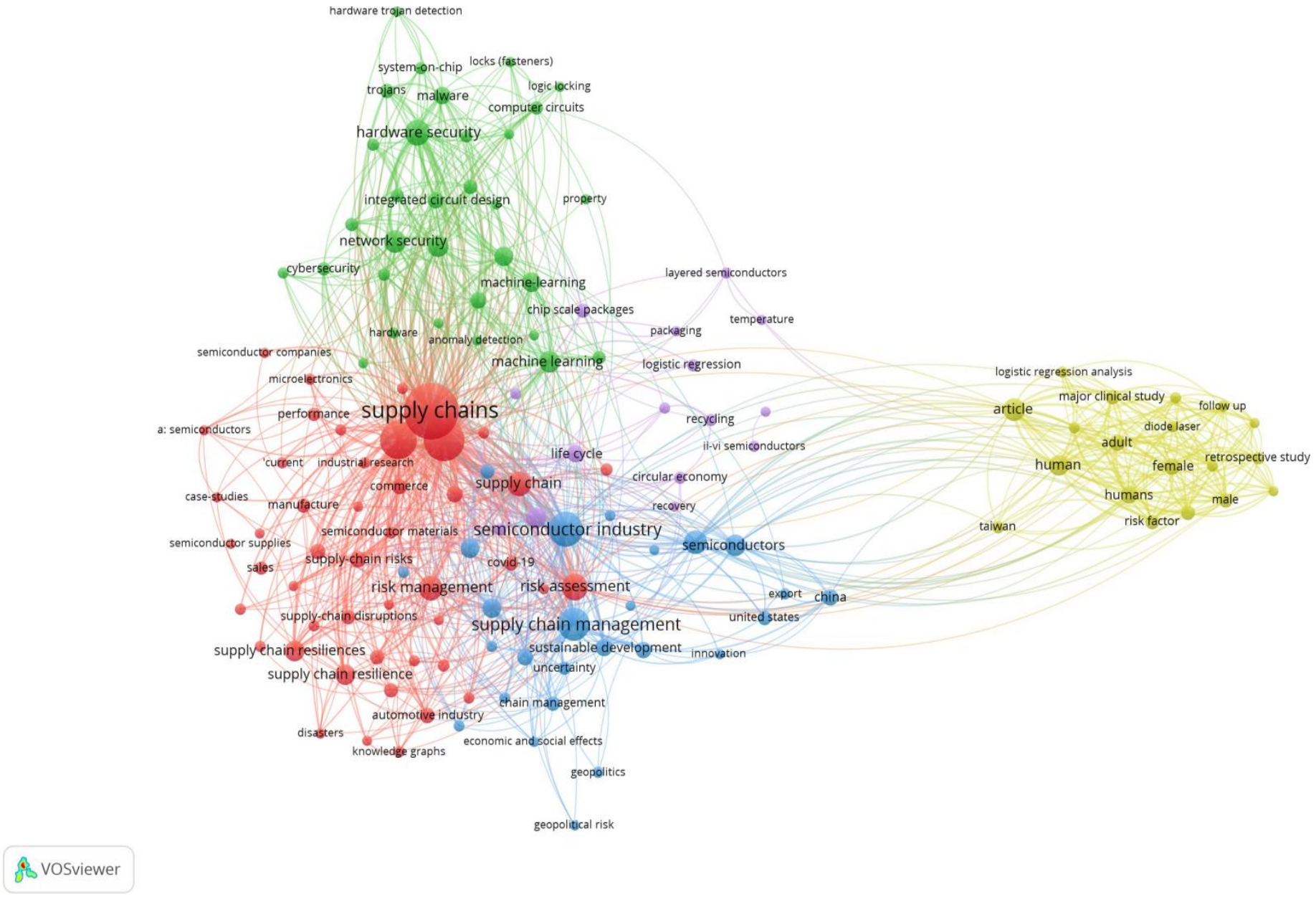


Figure 3. Literature clustering of methodology and supply chain keywords.

5. Semiconductor Supply Chain Disruption Recovery Framework

This section presents the proposed recovery framework (Figure 4), which organizes recovery strategies across four sequential response horizons—Detection, immediate, short-term, and long-term methods, followed by detection, immediate, short-term, and long-term phases across operational, collaborative, and regulatory tracks.

A semiconductor supply chain disruption unfolds not as a single event but as a trigger that propagates through four sequential horizons: Detection, Immediate, Short-Term, and Long-Term. In the Detection phase, the framework emphasizes visibility beyond first-tier suppliers because more than 30% to nearly 50% of disruptions originate below the first tier, where monitoring is often weakest [21]; multiplex analysis then integrate geopolitical, logistics, financial, and demand signals to distinguish localized shocks from systemic crises [13]. In parallel, while demand sensing tracks downstream needs in real time, helping to prevent both over-allocation and under-reaction [36]. Once a disruption is confirmed, the Immediate phase activates agile procurement to secure alternate sourcing within days [36], competitor collaboration to share capacity and reduce the risk of systemic failure, as demonstrated during the 2020–2022 chip shortage [37], and government prioritization to redirect scarce output toward critical sectors as occurred during COVID-19 [13].

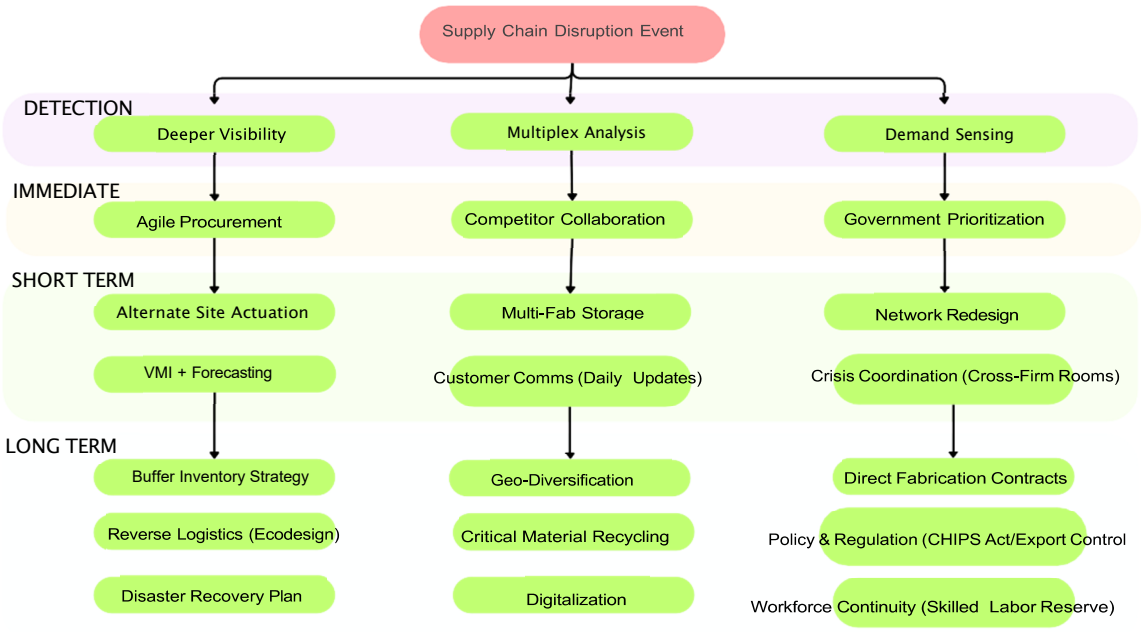


Figure 4. Phased recovery strategy framework for semiconductor supply chain disruptions across Detection, Immediate, Short-Term, and Long-Term horizons.

The Short-Term phase stabilizes the network structurally: alternate site actuation qualifies backup fabs in advance [8], multi-fab storage spreads inventory risk across sites [29], VMI paired with forecasting lets suppliers manage customer stock directly to curb the bullwhip effect [38], daily customer communications sustain trust and early warning [21], network redesign reduces concentration risk through new supplier qualification[19], and cross-firm coordination rooms translate government signals into allocation decisions [39].

The Long-Term phase focuses on institutionalizing recovery capabilities and strengthening structural resilience. Buffer inventories can provide additional protection against prolonged shortages, as demonstrated by firms such as Apple and Microsoft during the 2020–2022 shortages [8]. Reverse logistics and eco-design can support material recovery and resource efficiency [40]. Geographical diversification can reduce location-specific concentration risk, particularly in advanced semiconductor manufacturing [4]. Critical-material recycling can further reduce exposure to future supply disruptions and climate-related risks [13]. Digitalization provides the data infrastructure required to coordinate these recovery strategies [18], while long-term fabrication agreements can secure production capacity during periods of constrained supply [41]. Finally, policy instruments such as the CHIPS Act and export controls, supported by workforce-continuity investments, can strengthen the institutional foundations of long-term recovery [7,29]. Across all four horizons, three tracks run concurrently—Operational (inventory, digitalization, forecasting) [8,18], Collaborative (competitor sharing, VMI, coordination rooms) [37–39], and Regulatory (government prioritization, CHIPS Act, export controls, workforce policy) [7,13,29]—meaning mature resilience requires these three to move together within each phase, not in sequence.

5.1. Detection Phase

5.1.1. Deeper Visibility

The concept of deeper visibility refers to supplying chain participants being able to have visibility on conditions not only at the first tier of suppliers but also across second and third tier nodes; where most disruptions originate from but where they are rarely monitored or visible. Studies suggest more than 30 percent to almost 50 percent, of supply chain disruptions occur after first tier suppliers and within the deeper levels of the supply chain. To achieve deeper visibility requires investment into real-time tracking platforms, supplier data sharing agreements, and AI based tracking tools. Better supplier relationships, visibility into second and third tiers of suppliers, and shared intelligence on geopolitical risks, and material risks provide the industry with a better ability to detect disruptions prior to their escalation into crisis. Without this deeper visibility, businesses will still take a reactive position and will be unable to act until after a disruption has already propagated through the supply chain [21].

5.1.2. Multiplex Analysis

Multiplex analysis involves the concurrent assessment of disruption signals from various dimensions—geopolitical factors; logistics; finances; and demand—so that a complete picture of the emerging crisis can be created showing its extent and the ways in which it is interconnected with other crises.

Rather than considering threats to supply chains as isolated events, multiplex analysis creates an overall view of how each threat interacts with all other vulnerabilities present in the supply network. The Agentic AI framework has the capability to autonomously monitor, analyze and respond to all types of disruption within a broad supply chain, including being able to find new sources of news to identify disruptions, locating these disruptions within 2nd tier and 3rd tier suppliers, assessing their effect on the entire supplier network, and making recommendations on how to minimize them. Multiplex analysis allows decision makers to differentiate between localized shocks and systemic crises, thereby identifying the correct level and urgency needed in their response [13].

5.1.3. Demand Sensing

Tracking and interpreting end-user demand in real-time, to better predict how disruptions will affect downstream needs across various product categories and customer segments is referred to as demand sensing. In addition to planning and simulating scenarios for extreme disruption to supply or demand, organizations are also revisiting their just-in-time inventory model; developing digital twins of key parts of the supply chain will allow for deeper simulation/testing and create agility for the organization to respond quickly/efficiently to unexpected events. Demand sensing also helps to avoid both over-allocation of resources—for example, sending limited chips to low-priority products—and under-reaction—that is, demand increases for high-priority products such as in automotive or defense that are undetected until severe shortages occur [35,42].

5.2. Immediate Phase

5.2.1. Agile Procurement

Agile procurement is the ability to quickly adapt purchasing strategies immediately after a disruption, including sourcing alternative suppliers, making emergency purchases on the spot market and renegotiating lead times with current suppliers. Navigating the complexities of the semiconductor industry requires agility and foresight. Unforeseen changes in demand as well as geopolitical issues can cause interruptions in the delivery schedule and inventory level. To reduce these risks and maintain operational continuity, manufacturers need to incorporate resilience into their strategies. Agile procurement is characterized by its speed and willingness to pay additional costs; during times of crisis, continuity of supply is more important than optimizing unit cost; and businesses that have prequalified potential alternative suppliers can bring them online in days rather than months [36].

5.2.2. Competitor Collaboration

In the semiconductor supply chain, competitor collaborative activities involve sharing logistics infrastructure, inventory information, or capacities between competing firms to avoid a systemic failure of the industry as a whole during a crisis. Unlike previously, supply chain resilience is now a competitive advantage rather than only a risk management strategy. Moving forward, the industry will need to develop collaborative strategies to share playbooks and coordinate throughout the supply chain during extreme distress periods. In response to the chip shortage from 2020 to 2022, automotive OEMs and electronics companies shared informal discussions about capacity-sharing, as a production stop at one competitor could lead to a supplier failure for that competitor and

others. Competitor collaborative efforts involve having pre-established frameworks for building trust and antitrust-compliant methods of communication [37].

5.2.3. Government Prioritization

National authorities intervene to reallocate limited semiconductor production capacity to strategically important sectors, e.g., Defense, Health Care, Critical Infrastructure, during critical short-ages in semiconductors. Governments are increasingly acknowledging semiconductor technology to be of critical importance to national infrastructure and that, through targeted policy intervention during times of disruption, semiconductor manufacturers can refocus their manufacturing priorities on those sectors that would experience the greatest economic or national security ramifications from the failure to supply semiconductor product. Government intervention can occur in the form of emergency purchase mandates, export controls, and direct subsidies to semiconductor manufacturers to reorient production towards priority product. Importantly, this type of intervention was implemented during the COVID-19 pandemic when governments ordered semiconductor supply to be diverted from other electronic products to assure supply for ventilator and telecommunications equipment [13,43].

5.3. Short-Term Phase

5.3.1. Alternate Site Actuation

When a primary production facility goes down, the use of alternate site actuation is defined as the use of a secondary or backup facility to activate production in the absence of the primary production facility. In semiconductor manufacturing, activating alternate site actuation requires advance qualification and testing of an alternate facility (or 'fab') with the ability to produce goods with equivalent specifications/characteristics (e.g., physical, electrical) and it is technically difficult to find fabs that meet this requirement due to process specificity in semiconductor manufacturing. Therefore, one of the primary mitigation strategies for decreasing exposure to risk is to diversify and lower your reliance on single regions/supplying regions; geographically this will mean expanding your fabrication footprint to include, for example, US, Europe, Vietnam and Mexico. Alternate site actuation is maximally effective when executed with pre-existing dual-sourcing agreements and periodic small-volume production runs of the alternate site fab to confirm the fab is ready for activation [8].

5.3.2. Multi-Fab Storage

Storing fabric in multiple locations means storing unfinished and completed production at mul-tiple manufacturing sites, not just one. It also means there is less chance of all inventory at one site being affected if there is something happening in that area (example: natural disaster, power outage, or geopolitical event). Strategic inventory management requires holding some level of safety stocks of semi- or fully-manufactured parts and continually adjusting these as necessary to balance supply and total cost; for example, some parts would have a safety inventory while others would have enough inventory within established channels for substitutes. Multi-fab storage will increase the cost to hold products; however, it provides a significant cushion during the time between when a disruption occurs and when production is set up at an alternative location [29].

5.3.3. VMI + Forecasting

The term Vendor Managed Inventory (VMI) refers to a collaborative inventory management system whereby the supplier is responsible, rather than the end-user, for monitoring and replenishing customer/partner item stock levels based on shared real-time production and sales data. An example of this type of system might be an electronics manufacturer implementing a VMI program with their semiconductor manufacturers. This particular arrangement would provide semiconductor manufacturers with direct access to the electronics manufacturer's production schedules and forecast information; thus giving the semiconductor manufacturers the ability to adjust their pro-duction and delivery schedules based upon that information, thereby reducing production delays (i.e., due to parts shortages) while at the same time helping to minimize excess inventory. Utilizing advanced demand forecasting tools in conjunction with a VMI system can further increase the electronics manufacturer's ability to proactively manage inventory rather than reactively managing inventory due to the bullwhip effect that is often experienced during periods of semiconductor shortages throughout the semiconductor supply chain [38].

5.3.4. Customer Comms (Daily Updates)

Viewpoints in customer communication during a disruption is the systematic sharing of supply status, expected delivery dates, allocation decisions and recoverable milestones with all downstream customers on a daily basis. Clear and open communication serves both practical and relational purposes; it enables customers to modify their own production schedules due to new constraints, while also supporting trust through commercial relationships so they won't be damaged due to un-explained delays. Suppliers who maintain supply will typically find that they work with contracted vendors early in their planning processes by providing operators with real-world volume predictions, timing needs, and flexibility areas; when transparent communications exist, trust is increased and will often guide allocation in constrained markets. Early warning of escalating material shortages is gained from daily updates [21].

5.3.5. Network Redesign

Network redesign involves redefining the supply chain's topological structure. This includes the supplier relationships that are established, the locations of manufacturing facilities, the logistics flow, and the positioning of inventory in response to the exploitability of vulnerabilities present after the occurrence of a disruptive event. Network redesign is distinct from incremental changes since it typically involves significant architectural changes designed to decrease systemic concentration risk. Supply chain network design represents a complex multi-objective design optimization problem requiring trade-offs among competing objectives in order to make strategic and tactical decisions related to supplier selection, facility location, facility allocation and inventory level, all subject to several kinds of constraints and uncertainties. The increased priority on sustainability and resilience related to supply chains has also impacted these objective balances. Typically, during the short-term recovery phase of a supply chain's recovery, network redesigns will focus on qualifying new suppliers and redistributing production across a wider geographic area [19].

5.3.6. Crisis Coordination (Cross-Firm Rooms)

Crisis coordination via cross-firm coordination rooms means establishing formal multi-stakeholder coordination mechanisms (both virtual and physical) in which representatives of competing companies, suppliers, customers, and government organizations can meet together in real-time to collectively manage disruptions to their supply chains. As a result of sharing consistent intelligence across all stakeholders in the supply chain, stakeholders will be able to identify areas of shared

vulnerability and develop collaborative strategies to mitigate those vulnerabilities. Additionally, stakeholders may become more resilient over time as they implement strategies for diversified sourcing and establish shared contingency planning mechanisms. Finally, cross-firm coordination rooms will be the basis of enabling stakeholders to make collective decisions on a faster basis, prevent competitive hoarding behavior that would aggravate supply chain shortages, and provide a mechanism for translating government prioritization signals into operational allocation decisions for each company [39,44].

5.4. Long-Term Phase

5.4.1. Buffer Inventory Strategy

The practice of holding excess safety stock over and above the operational minimum levels allows semiconductor manufacturers to mitigate future supply chain risks. For example, in 2020 and 2022, Apple responded to increasing shortages of critical semiconductor components by adding additional strategic inventory. This enabled Apple to maintain a consistent supply of semiconductor components for the production of iPhones and avoid the potential disruption of production stopping and delaying orders; in a similar fashion, Microsoft used strategic inventory to successfully manage semiconductor shortages and maintain a consistent supply of gaming consoles. The transition from just-in-time inventory management to buffer inventory management marks a significant strategic shift in the semiconductor industry, as manufacturers accept the additional holding costs associated with manufacturing being able to maintain a steady supply. The implementation of effective buffer inventory strategies requires a process for accurately sensing demand and performing frequent re-views to prevent newly manufactured products from becoming obsolete, given that chip technology is rapidly evolving [8].

5.4.2. Reverse Logistics (Ecodesign)

Reverse logistics refers to the planned recovery of semiconductor materials and components from end-of-life products to support manufacturers with reclaiming/reusing semiconductor materials and components throughout their supply chain, while utilizing Ecodesign principles. Ecodesign incorporates dismantling and recycling features into the chip and PCB designs, providing a more efficient method of recovering materials. In addition, innovative methods of recycling or refurbishing semiconductor components, such as a unified collection center to facilitate the collection and refurbishment of semiconductor components that can then be reused either in their original configuration or in other applications, can help fill the gap in a constrained supply situation; while not a total solution, these types of programs can provide short-term stability to a manufacturer's overall supply and buy manufacturers some time to make longer-term adjustments. Reverse logistics has a role in sustainability as it reduces reliance on virgin raw materials [40].

5.4.3. Disaster Recovery Plan

A disaster recovery plan describes how to respond to major disruption events in the semiconductor supply chain. The plan includes how to activate the protocol, what actions are taken, who's responsible, how communication will occur and how resources will be deployed. The protocol is a pre-determined operationally validated document, which will allow a faster, more coordinated approach in the event of a disruption as opposed to an ad hoc response. In developing strategic responses to supply chain disruptions, simulating and planning for extreme supply/demand disruptions has become a priority. Digital twins can be created for critical supply chain locations to better simulate and test scenarios, allowing for quicker and more informed responses to unanticipated events. Disaster recovery plans include responses for various disruption types, including natural disasters, cyber-attacks, geopolitical shocks and supplier bankruptcies [27].

5.4.4. Geo-Diversification

Geographic diversification of semiconductor manufacturing is the purposeful diversifying of semiconductor manufacturing, assembly, and materials capacity across numerous regions/countries in order to lower the systemic risk associated with being concentrated in any one geography. For instance, on April 3, 2024 when a magnitude 7.4 earthquake occurred along Taiwan's fault line, production at Taiwan's most advanced semiconductor fabrication plants were halted; and TSMC evacuated parts of their facilities doing 90 percent of the world's advanced chip production, exposing the fact that geographic diversification alone cannot resolve the semiconductor resilience issue given that Taiwan is responsible for more than 60 percent of the world's semiconductor supply and 92 percent of the world's advanced chip production. In response, leading-edge wafer fabrication capacity is expected to see tremendous growth outside of only Taiwan and South Korea as new manufacturing, assembly, and materials facilities develop in the US, Europe, and Japan over the next 10 years [4].

5.4.5. Critical Material Recycling

The term critical material recycling designates the retrieval and processing of rare and essential raw materials such as gallium, germanium, indium, and rare earth elements that are contained primarily in used semiconductors and their manufacturing wastes. Using these strategies, semiconductor manufacturers can lessen their need for using newly mined materials and decrease the concentration of foreign suppliers. By 2030, an estimated one-third of the world's chip assembly operations could experience climate-related disruptions, and semiconductor manufacturers are implementing a variety of operating strategies to address these issues, including water reclamation practices, acquiring alternative energy sources, and incorporating environmentally friendly processes into their manufacturing facilities. However, the availability of certain raw materials required to produce chips, such as copper, could be compromised due to drought conditions and will present additional challenges for the semiconductor industry. The use of critical material re-cycling to create a more diverse and resilient supply chain reduces the reliance on raw materials from politically sensitive zones and supports sustainable recycling practices (defined by the circular economy) [13].

5.4.6. Digitalization

In order to improve the visibility, agility, predictive ability and coordination of the whole supply base through the use of new digital technologies—including AI, blockchains, Internet of Things (IoT) enabled sensors, and digital twins—digitalization in the semiconductor value chain refers to bringing in advanced digital technology to help achieve these improvements. Some examples of digitalization within the semiconductor supply chain involve

IoT enabled sensors to help streamline operations (reduce waste) and enable better decision making through AI driven demand forecasting, blockchain-based transparent tracking of parts, etc. These solutions will improve the accuracy by which AI can predict inventory requirements; decrease waste; and ensure timely delivery. As international markets continue to experience increased levels of uncertainty, the importance of using digital tools to create resilient supply chains that can quickly react to sudden disruptions has become increasingly important. Digitalization is also a critical enabler for nearly all of the long-term recovery strategies since it provides the underlying data infrastructure necessary for making real-time decisions, performing scenario simulations, and collaborating across firms [18].

5.4.7. Long-Term Fabrication Agreements for Supply Certainty

Direct fabrication contracts are agreements made over a long term between semiconductor foundries and chip customers (typically the large OEMs or systems integrators who make chips for others). The chip customers enter into these agreements to guarantee themselves some of the wafer capacity in return for volume commitments or co-investment (i.e., putting up capital). In some cases, companies might evaluate the option for a binding take-or-pay contract which allows them to accept a quantity of chips within a specified amount of time or pay a fee if they do not, thus providing more accurate alignment of chip demand to manufacturing capacity; it may also give customers the opportunity to co-invest with semiconductor manufacturers in projects designed to increase fab capacity which reduces or eliminates the manufacturer's upfront capital investment. Direct fabrication contracts help to eliminate the uncertainty about allocation during shortages and give the foundry the ability to determine the amount of capital necessary to make major capital expenditures [41].

5.4.8. Policy Regulation (CHIPS Act/Export Control)

The various methods of intervention by governments through regulation and policy are referred to as policy and regulatory intervention; these include: subsidies; tax incentives; export restrictions; and trade barriers; all of which are used by governments to help alter the competitive conditions of the global semiconductor industry, to develop national resilience against supply chain disruptions; and to assist in creating alliances with others who are developing/using semiconductor technology. Passed by Congress in August 2022, the CHIPS and Science Act allocated 52 billion dollars to encourage companies to manufacture, research and develop semiconductors in the U.S.; this will lead to an additional 450 billion dollars in private sector investment and will result in over 200 percent increase in the U.S. semiconductor fabrication (fab) capacity by 2032; the European Chips Act seeks to mobilize over €43 billion to strengthen the position of Europe to capture a 20 percent share of the global semiconductor market by 2030. Export restrictions, such as the U.S. restrictions on advanced semiconductor exports to China, are a coercive adjunct to an industrial policy based on subsidy approaches [7].

5.4.9. Workforce Continuity (Skilled Labor Reserve)

Developing, maintaining, and steadily expanding the pool of highly skilled technical workers needed for the operation, maintenance, and innovation of semiconductor manufacturing and design facilities is a long-term strategy. High factory usage rates; the ability to attract long-term customers; and establishing a strong ecosystem of skilled labor and infrastructure necessitate efficient planning; if not thoughtfully planned, over-capacity and downward price pressure will negatively affect profits, thus making the development of the workforce ecosystem as crucial as investing in capital. There are positions and projects at semiconductor manufacturing facilities that require individuals with backgrounds from PhD-level scientists in material sciences to precision maintenance technicians, and the lack of available qualified individuals will cause delays in ramping up production at facilities even with 100 percent committed capital. Continuous investment in partnerships with universities, apprenticeship programs, and reforming immigration policy is critical to preserving the labor market for the long term [29].

6. Discussion

Building upon the proposed Semiconductor Supply Chain Recovery Framework, this study devel-ops a Recovery Strategy Applicability Matrix to operationalize the identified recovery strategies across different organizational contexts. The matrix was derived through a synthesis of the reviewed literature rather than an arbitrary classification of firm behavior.

In this study, a Recovery Applicability Matrix is developed which systematically maps recovery strategies onto the context of an organization. The matrix enables cross-tabulation of firm archetypes against recovery time horizons and identifies feasible recovery strategies for four distinct firm archetypes: Small and Medium-sized

Enterprises (SMEs), capital-rich start-ups, medium-sized enterprises, and government-backed enterprises. These archetypes were selected because they represent structurally distinct resource and institutional positions. SMEs typically operate under limited financial resources; capital-rich start-ups possess relatively high funding but comparatively limited in-house manufacturing capabilities; medium-sized firms occupy an intermediate resource position; and government-backed enterprises benefit from stronger institutional and policy support. Recovery is divided into Immediate, Short-Term, and Long-Term horizons because the reviewed literature (Section 5.1) indicates that the feasibility and priority of recovery strategies change as the disruption timeline extends. Each cell of the matrix therefore represents a distinct strategic position and reflects the varying recovery capacities of different firm types. Resource and institutional constraints, together with market leverage, provide the basis for determining which specific interventions can be implemented by each firm during a disruption [8,27].

In Figure 5, the rows represent recovery time horizon, the columns represent firm capability archetype, and each cell represents the recommended recovery priority for a specific combination of firm type and recovery horizon. The strategies assigned to each firm archetype reflect differences in financial resources, institutional support, operational flexibility and feasibility. The strategy of buffer inventory and rapid tiers mapping is closely linked to resource poor SMEs because their lack of financial resources limits their capacity to implement flexible sourcing strategies and large-scale structural investments. On the other hand, capital abundant start-ups can use their financial resources to replace production techniques and implement flexible sourcing solutions, although their manufacturing capabilities are limited. Government-supported companies can rely more on policy-driven measures and coordinated resource allocation due to greater support by institutions.

The matrix proposed is conceptual and literature-derived; therefore, empirical validation through case studies or evaluation by the experts is a relevant aspect of further research. The distinctive contribution of this study lies in integrating firm characteristics with recovery time horizons rather than treating recovery strategies as universally applicable across organizations. The proposed recovery strategy applicability matrix therefore connects three dimensions that are typically considered separately: firm resource and institutional capacity, the temporal stage of disruption recovery, and the feasibility and priority of specific recovery strategies. This integration complements the Semiconductor Supply Chain Recovery Framework by translating its general recovery strategies into context-specific priorities for heterogeneous semiconductor supply-chain organizations. The abbreviations used for the firm capability archetypes in the Recovery Strategy Applicability Matrix are summarized in Table 1.

The findings of this review drawn from bibliometric analysis of 344 documents and synthesized into the proposed Semiconductor Supply Chain Recovery Framework (SSCRF) carry implications that extend beyond the immediate scope of the literature synthesis itself. This is, to the authors' knowledge, the first framework to integrate detection-stage sensing, phased operational response, and firm-differentiated recovery prioritization into a single, empirically grounded structure for the semiconductor sector. Because recovery-specific strategies remain comparatively underexplored relative to resilience research [2,22], the contribution of this study is best understood not only as a mapping exercise but as a foundation from which scholars, practitioners, and policymakers can each draw distinct, actionable conclusions. The following subsections discuss the research, managerial, and social implications of these contributions.

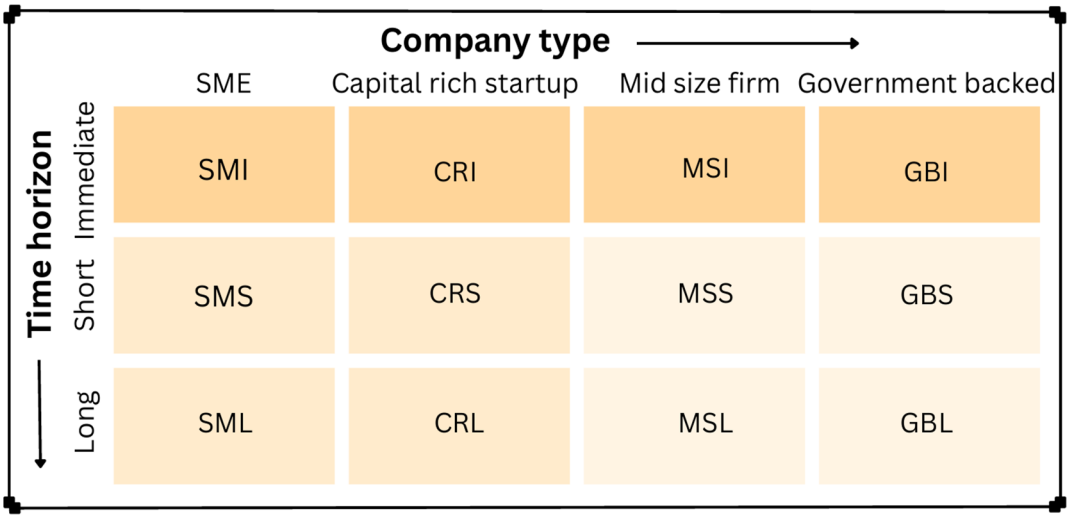


Figure 5. Recovery strategy applicability matrix mapping firm archetypes against disruption response time horizons in the semiconductor supply chain.

Table 1. Company archetype abbreviations and strategic recovery characteristics in the semiconductor supply chain recovery matrix.

Code	Full Form	Description
SMI	Small/Medium Enterprise—Immediate Recovery	This archetype reflects SMEs' limited financial resources and weak supplier leverage; buffer stock and rapid tier mapping demand minimal capital outlay while offering immediate visibility into disrupted nodes, matching low-cost, low-complexity interventions to constrained short-term recovery capacity [4,8].
SMS	Small/Medium Enterprise—Short-Term Recovery	Given that SMEs cannot easily secure alternative suppliers under pressure, design-for-substitution reuses existing product architecture with available components, avoiding costly qualification of new sourcing relationships and making it the most feasible option within their constrained sourcing options [18,42].
SML	Small/Medium Enterprise—Long-Term Recovery	Because SMEs cannot fund new fabrication capacity, dual geographic sourcing diversifies risk exposure at moderate cost, gradually reducing dependency on a single region without requiring the heavy capital investment long-term recovery strategies typically demand [9,17].
CRI	Capital-Rich Startup—Immediate Recovery	Positioned here because capital-rich startups possess funding but lack established manufacturing relationships; spot-market arbitrage converts financial strength directly into procurement speed, letting them outbid competitors for scarce inventory when formal supplier agreements remain unavailable [4,36].
CRS	Capital-Rich Startup—Short-Term Recovery	Reflecting the fact that startups have capital but limited in-house fabrication capability, accelerated design-for-substitution leverages flexible supplier networks and engineering resources their funding can buy, converting financial strength into rapid redesign rather than reliance on manufacturing relationships [18,42].
CRL	Capital-Rich Startup—Long-Term Recovery	Justified by the fact that startups can fund advanced technology adoption despite lacking manufacturing scale; dual-source qualification paired with AI sentinel monitoring builds structural resilience and predictive visibility, converting capital advantage into long-term supply chain intelligence and diversification [9,21].
MSI	Mid-Size Firm—Immediate Recovery	Rooted in the fact that mid-size firms hold moderate resources between SMEs and startups, buffer stock activation stabilizes upstream flows using existing inventory management capability, offering a balanced, immediately deployable response without requiring extensive negotiation or new capital investment [4,8].
MSS	Mid-Size Firm—Short-Term Recovery	Explained by mid-size firms possessing enough engineering capacity to redesign products around available alternatives; redesigning around second sources balances feasibility and impact, reflecting their intermediate resource position between constrained SMEs and highly flexible capital-rich startups [13,42].
MSL	Mid-Size Firm—Long-Term Recovery	Grounded in mid-size firms' capacity to invest moderately in digital tools and dual-sourcing, combining AI sentinel monitoring with geo-distributed dual-fab strategies builds structural resilience proportionate to their intermediate capital base, operational scale, and moderate institutional support [9,21].
GBI	Government-Backed Enterprise—Immediate Recovery	Attributable to government-backed enterprises' access to institutional and policy support, activating CHIPS Act vouchers and conducting national supply audits leverages regulatory access unavailable to private firms, translating policy backing directly into immediate operational continuity [2,6].
GBS	Government-Backed Enterprise—Short-Term Recovery	Driven by government-backed firms' ability to convene and enforce multi-stakeholder cooperation, mandating consortium alliances accelerates collective recovery by leveraging regulatory authority to coordinate competitors and suppliers—a capability the other three private archetypes structurally lack [13,39].
GBL	Government-Backed Enterprise—Long-Term Recovery	Warranted since only government-backed enterprises hold policy-making authority, driving export control reform alongside national geo-dual sourcing policy reshapes the structural environment for the entire industry, reflecting their unique institutional capacity for long-term systemic change [2,9,40].

6.1. Research Implications

This study extends semiconductor supply-chain resilience research by explicitly positioning recovery as a distinct but interdependent research construct rather than solely as a downstream outcome of resilience. The bibliometric analysis of 344 publications provides evidence of the comparatively limited attention given to recovery-oriented research. Building on this evidence, the SSCRF introduces a structured temporal perspective by organizing recovery into Detection, Immediate, Short-Term, and Long-Term horizons and linking these horizons to Operational, Collaborative, and Regulatory tracks. This provides researchers with a structured basis for examining how recovery strategies evolve over the course of a disruption. A further contribution is the Recovery Strategy Applicability Matrix (Figure 5), which connects recovery strategies with differences in firm resource and institutional capacity. This firm-differentiated perspective creates opportunities for future empirical research to examine whether the feasibility and

effectiveness of particular recovery strategies vary systematically across organizational types. Because the proposed framework and matrix are literature-derived and conceptual, future research should validate them through case studies, expert assessment, simulation modelling, or survey-based research and develop standardized metrics for recovery speed, supplier reconfiguration, and long-term network stability.

6.2. Managerial Implications

For practitioners, the SSCRF and Recovery Strategy Applicability Matrix (Figure 5) provide a structured decision-support perspective for aligning recovery strategies with both disruption horizons and organizational capabilities. Rather than applying a uniform recovery playbook, the framework enables managers to consider how resource availability, institutional support, operational flexibility, and implementation feasibility influence the prioritization of recovery actions. For resource-constrained SMEs, the matrix emphasizes relatively feasible measures such as buffer inventory and rapid tier mapping, while capital-rich start-ups may have greater scope to consider design substitutability and flexible sourcing. Government-backed enterprises may have greater capacity to leverage policy support and coordinated capacity allocation. The temporal dimension of the matrix also indicates that recovery priorities may evolve from immediate stabilization toward longer-term structural interventions as disruption duration increases. The framework therefore provides managers with a structured basis for contingency planning and recovery prioritization while recognizing that the proposed classifications require organization-specific assessment and empirical validation. In particular, multi-tier visibility, supplier prequalification, and coordination mechanisms can be considered as pre-disruption capabilities that improve the ability of firms to activate recovery strategies when disruption occurs.

6.3. Social Implications

Beyond firm-level performance, semiconductor supply chain recovery carries broader societal and policy implications given the sector's role in national security, healthcare, and critical infrastructure. Policy interventions such as the CHIPS Act and the EU Chips Act illustrate how recovery capacity is increasingly treated as a matter of public interest rather than purely private risk management, However, these interventions affect stakeholders differently: governments influence policy timing and subsidy allocation, firms may gain access to financial and institutional support, and downstream industries may continue to face adjustment costs while such interventions take effect. The framework's emphasis on workforce continuity highlights that recovery speed is constrained not only by capital but by the availability of specialized technical labor, a constraint compounded by demographic pressures—an ageing skilled workforce and slowing graduate pipelines in key semiconductor-producing regions—that shape the business environment and influence long-term recovery capacity, implying that sustained investment in education and training pipelines carries societal as well as commercial returns. Recovery is also influenced by external events and stakeholders beyond the firm's direct control, including geopolitical conflicts, export restrictions, natural disasters, governments, and regulatory institutions. These factors can affect firms differently depending on their geographic exposure, resource availability, supplier structure, and institutional support, highlighting the importance of considering external conditions when applying the SSCRF across different firm archetypes. Similarly, embedding sustainability into recovery through critical-material recycling and eco-design can reduce dependence on environmentally and geopolitically sensitive raw material sources, meaning that recovery-oriented investment decisions carry consequences for environmental resilience and geopolitical stability that reach well beyond individual firms or their immediate supply networks.

7. Conclusions

This research aims to address an important and pressing gap in supply chain studies: the lack of a unified system for assessing and recovering semiconductor supply chains when existing resilience capabilities are no longer sufficient. The semiconductor industry remains among the most strategically important but also the most vulnerable parts of the worldwide industrial base. To establish the extent of this gap, a systematic review of the existing literature was performed based on 344 publications reviewed according to the PRISMA Guidelines and analyzed through VOS viewer. The analysis revealed that recovery is much less researched than resilience in the literature. While resilience studies create dense and interconnected clusters in published findings, recovery-related subjects remain dispersed and undeveloped, leaving practitioners without clear guidance on how to resume operations once existing resilience measures are no longer sufficient to absorb the disruption.

To address this gap, the research proposes the Semiconductor Supply Chain Recovery Framework, which categorizes recovery actions across four successive response horizons: Detection, Immediate, Short-Term and Long-Term and three parallel tracks of recovery action: Operational, Collaborative, and Regulatory. The

framework emphasizes that no single player, whether a company, a rival, or the government, can restore a disrupted supply chain by relying upon its own actions alone. Building on this framework, the study's second key contribution is the Recovery Strategy Applicability Matrix, which maps recovery actions onto four enterprise archetypes: resource-constrained SMEs, capital-rich start-ups, mid-sized companies, and government-backed entities, according to their financial means, institutional support, and operational flexibility.

Together, these contributions point toward several directions for future research. Since the proposed framework is conceptual and has not undergone empirical validation, it is advisable for upcoming studies to validate the model through survey-based studies of companies that have survived an actual disruption. The development of standardized recovery metrics can further aid the discipline in transitioning from qualitative to quantitative knowledge. Other promising directions include investigating the use of emerging technologies, such as AI-enabled and agentic simulations, in line with the framework's model of monitoring and coordination, and carrying out cross-country comparisons of the recovery effects produced by regulatory tools such as the CHIPS Act and the EU Chips Act.

The study also has several limitations. First, the bibliometric analysis is based only on the Scopus database; while Scopus offers considerable coverage of the peer-reviewed literature, it may have excluded grey literature and industry reports that could also help explain recovery in various ways. Second, the Recovery Strategy Applicability Matrix was developed using qualitative synthesis of the reviewed literature rather than case studies, so the relationships it presents should be treated as conceptual and testable propositions rather than established conclusions. Finally, the results of the keyword co-occurrence analysis are dependent on the keyword-cleaning procedure used in data preparation; a different cleaning technique could therefore yield a different network structure and a different perspective on the research topic.

Author Contributions

T.V.: conceptualization, methodology, software, writing; G.S.: conceptualization methodology, writing, editing; B.E.N.: conceptualization, methodology, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not Applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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