

Real-Time Visibility for Building Adaptive Resilience

Slawomir Wycislak^{#1}, Atif Akhtar^{*2}

[#]*Institute of Economics, Finance and Management, Jagiellonian University,
ul. prof. S. Łojasiewicza 4, 30-348 Kraków, Poland*

^{*}*Johns Hopkins University, United States*

¹slawomir.wycislak@uj.edu.pl

²atifakhtar22@gmail.com

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Abstract— Supply chain resilience has become critical in today's volatile global landscape. Recent disruptions have exposed vulnerabilities in interconnected supply networks, highlighting the need for new approaches to managing complex, rapidly evolving challenges. This research investigates how real-time visibility facilitates adaptive resilience in global supply chains through an integrated theoretical framework. Using a mixed-method approach, we analyze five major recent supply chain disruptions including the Red Sea crisis, Panama Canal drought, COVID-19 outbreaks, Baltimore bridge collapse, Israel-Iran conflict. We develop the Real-Time Adaptive Resilience (RTAR) model, a four-layer framework that explains how visibility transforms data into adaptive capabilities. Our findings reveal three key mechanisms through which real-time visibility enhances resilience: information velocity, system-wide transparency, and predictive capability. The research contributes to supply chain management theory by integrating Resource-Based View, Dynamic Capabilities, and Systems Dynamics perspectives while providing practical guidance for building adaptive supply chain capabilities.

Keywords— Supply chain resilience, real-time visibility, adaptive capabilities, disruption management, systems dynamics, dynamic capabilities

1. Introduction

Supply chain resilience has become critical in today's volatile global landscape. Recent disruptions—from pandemics to geopolitical tensions—have exposed the vulnerabilities of interconnected supply networks [1]; [2]. Organizations now recognize that traditional

reactive approaches are insufficient for managing complex, rapidly evolving disruptions.

Real-time visibility offers a solution. Defined as the capability of 'being perceived by the eye or mind' [3], p. 248, supply chain visibility enables organizations to monitor, understand, and respond to disruptions as they unfold. Research demonstrates that real-time visibility helps mitigate disruptions like the bullwhip effect—where small demand changes amplify upstream through the supply chain [4] (Dominguez et al., 2015; Sodhi & Tang, 2019); [5]; [6]; [7]; [8].

Despite extensive research on supply chain visibility, significant gaps remain. Current literature lacks a unified framework explaining how real-time visibility enhances resilience across different disruption types. This fragmentation limits our understanding of visibility's role in building adaptive supply chain capabilities.

This research addresses a fundamental question: How does real-time visibility in global supply chains facilitate emergent behaviors and self-organization to enhance resilience against disruptions?

By examining five major recent disruptions through an integrated theoretical lens, we develop the Real-Time Adaptive Resilience (RTAR) model—a comprehensive framework that explains how visibility transforms data into adaptive capabilities.

2. Literature Review

2.1 The Evolution of Supply Chain Visibility Research

The evolution of supply chain visibility (SCV) research reflects a growing recognition of its importance in modern supply chain management. In the early 2000s, research primarily focused on basic concepts and definitions. [9] were among the first to discuss determinants that hinder SCV, including interoperability insufficiencies, imprecise data, and constrained access to persistent information.

The mid-2000s saw a shift towards a more comprehensive understanding of SCV and its role in supply chain management. [10] made significant contributions by emphasizing the importance of both technology-based factors, like IT systems and data sharing protocols, and non-technology-based factors, such as trust and commitment, in enhancing visibility. This research highlighted the multifaceted nature of SCV and set the stage for more nuanced investigations in the following years. The recognition of these diverse factors influencing SCV marked a crucial step in the evolution of research in this area.

As research on SCV progressed, scholars began to explore its relationship with supply chain resilience. [11] conducted a study focusing on two critical resources that impact SCV: connectivity and information sharing. Their research demonstrated that these factors not only enhanced visibility but also contributed to supply chain resilience. This connection between visibility and resilience became a significant focus of subsequent studies, as researchers recognized the potential of SCV to mitigate risks and improve supply chain performance in the face of disruptions.

The late 2010s and early 2020s saw a surge in research exploring the role of emerging technologies in enhancing SCV and resilience. [12] and [13] investigated the potential of Internet of Things (IoT) and data-driven technologies in improving SCV. These studies highlighted how advanced technologies could provide real-time data and analytics, enabling more proactive and responsive supply chain management. The integration of these technologies into SCV research marked a significant evolution in the field, reflecting the broader digital transformation occurring in supply chain management.

Recent research has increasingly focused on the complex interplay between SCV, resilience, and various organizational and environmental factors. [14] introduced a novel perspective by arguing

that the level of product complexity within an organization's environment can influence the effectiveness of upstream SCV in achieving sustainable performance outcomes. This research exemplifies the trend towards more nuanced and context-specific investigations of SCV and resilience. By considering factors such as product complexity, researchers are developing a more comprehensive understanding of how SCV contributes to supply chain resilience in different contexts.

The evolution of research on SCV and resilience has also been characterized by an increasing emphasis on empirical studies and quantitative assessments. While early research was largely conceptual, recent years have seen a growing number of studies attempting to quantify the benefits of SCV and its impact on supply chain resilience. However, as noted by [15], there remains a need for more research on the long-term implications of increased visibility on supply chain performance. This gap in the literature represents an important area for future research, as understanding these long-term effects is crucial for organizations considering investments in SCV initiatives.

The evolution of research on SCV and resilience reflects a growing recognition of their importance in modern supply chain management. From early conceptual studies to recent empirical investigations, the field has progressed toward a more nuanced and comprehensive understanding of these concepts. As supply chains continue to face increasing complexity and disruption, further research in this area will be crucial for developing effective strategies to enhance visibility and resilience in global supply networks.

2.2 Theoretical Foundations

Multiple theoretical perspectives contribute to our understanding of supply chain visibility and resilience. The Resource-Based View (RBV) positions visibility capabilities as strategic assets that create competitive advantage through information sharing and connectivity enhancement, though this approach has been criticized for its static view of resources [16]. Recent research by [17] supports this theoretical foundation by demonstrating how leading enterprises leverage technology solutions to overcome visibility challenges and achieve operational excellence, reinforcing the strategic value of visibility investments. Dynamic Capabilities Theory extends this framework by focusing on how organizations reconfigure resources in changing environments, particularly emphasizing supply chain reconfigurability and sensing

capabilities, despite measurement challenges in practical application [18].

Resource Dependence Theory (RDT) provides insights into managing external resource dependencies through interorganizational trust and joint governance mechanisms, although it tends to oversimplify complex supply chain relationships [19]; [20]. Organizational Information Processing Theory (OIPT) offers valuable perspectives on how visibility capabilities and internal integration reduce uncertainty through enhanced information processing, though its operational focus remains limited. [21]; [22]; [23]. Contingency Theory emphasizes achieving performance through alignment between internal capabilities and external environmental factors, optimizing supply chain configuration while struggling to balance stability and change requirements [24]; [25]; [26].

Cultural Dimension Theory (CDT) adds another layer by examining how national cultural values influence visibility behaviors and practices, though its generalizability across diverse supply chain contexts remains limited. Each theoretical lens provides unique insights while also presenting specific limitations that must be considered when developing comprehensive visibility strategies [27]; [15].

Systems Dynamics offers additional insights by modeling how information flows through supply networks over time. This approach reveals non-intuitive outcomes from feedback loops and time delays (Srinivasan & Swink, 2018). When integrated with RBV, Systems Dynamics shows how visibility investments create long-term resilience capabilities (Ivanov & Dolgui, 2019).

3. Methodology

3.1 Research Design

This study employs a mixed-method approach combining multiple case studies with quantitative analysis. We selected five major supply chain disruptions from the past two years, each representing different causal factors:

Selection Criteria:

- Occurred within the past two years
- Significant global supply chain impacts
- Diverse disruption types (geopolitical, environmental, health, infrastructure)
- Substantial real-time data availability/

3.2 Data Collection

Primary Data: We conducted extensive interviews with a Project44 senior manager over six months. Project44 provides supply chain visibility solutions globally, offering unique insights into real-time disruption management. Each bi-weekly interview lasted 60-90 minutes, focusing on:

- Real-time data utilization during specific disruptions
- Adaptive strategies employed by supply chain actors
- Disruption propagation patterns
- Technical aspects of visibility systems

Secondary Data: We collected quantitative metrics from visibility platforms, industry reports, academic publications, and news sources documenting each disruption.

3.3 Data Analysis

Thematic Analysis: Interview transcripts were coded using NVivo 12, employing both theory-driven and data-driven codes to identify patterns.

Time Series Analysis: Quantitative data on shipping routes, vessel locations, and transit times revealed disruption impacts and recovery patterns.

Cross-Case Synthesis: We compared patterns across disruption types to identify common dynamics and context-specific factors.

Systems Dynamics Mapping: Causal loop diagrams mapped feedback mechanisms in disruption propagation and response.

4. The RTAR (Real-Time Adaptive Resilience) Model

The Real-Time Adaptive Resilience (RTAR) model provides a comprehensive framework for understanding how real-time visibility enhances supply chain resilience. Figure 2 illustrates the model's four interconnected layers.

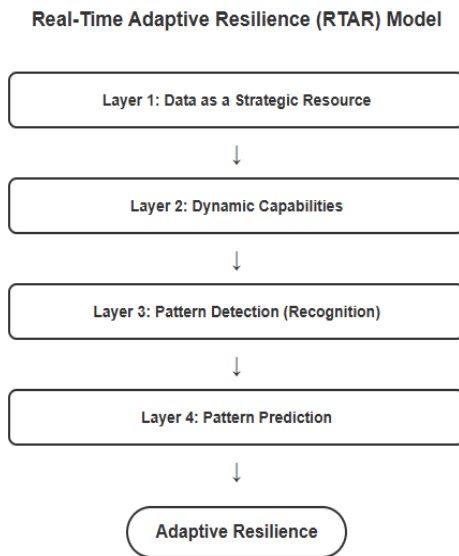


Figure 1. Real-Time Visibility Resilience Model.

3.1 Layer 1: Data as Strategic Resource

The foundation layer treats real-time data as a strategic asset. This includes:

Integrated Data Sources: Vessel locations, IoT sensors, environmental conditions, satellite tracking, and policy monitoring systems provide comprehensive situational awareness.

Data Quality Dimensions: Accuracy, timeliness, completeness, and accessibility determine the strategic value of visibility data.

Strategic Value Creation: High-quality real-time data enables enhanced decision-making, situational awareness, and anticipatory insights.

This layer aligns with the Resource-Based View by positioning visibility data as valuable, rare, and difficult to imitate—creating competitive advantage through superior disruption response.

3.2 Layer 2: Dynamic Capabilities

Building on the data foundation, Layer 2 encompasses organizational capabilities that transform information into action:

Adaptive Routing: Rapidly modifying transportation routes based on real-time conditions.

Operational Flexibility: Adjusting production and distribution processes to maintain continuity

Capacity Management: Dynamically reallocating resources to address bottlenecks

Risk Assessment: Continuously evaluating and mitigating emerging threats

Collaborative Coordination: Working with supply chain partners for system-wide responses. These capabilities enable organizations to reconfigure resources dynamically, creating adaptive capacity that enhances resilience.

3.3 Layer 3: Pattern Recognition

Layer 3 applies systems dynamics principles to identify complex supply chain patterns:

Cascading Effects: How disruptions propagate through networks

Feedback Loops: Reinforcing and balancing mechanisms in system responses

Threshold Effects: Critical points where system behavior changes dramatically

Adaptive Cycles: Patterns of stability, disruption, reorganization, and renewal

Temporal Dynamics: Time-delayed impacts of disruptions and responses

This layer enables organizations to recognize emergent patterns, providing the foundation for predictive capabilities.

3.4 Layer 4: Pattern Prediction

The highest layer focuses on anticipating future system behavior:

Goal-Seeking Behavior: Predicting how systems adjust toward equilibrium

Oscillation Patterns: Anticipating cyclical variations following disruptions

S-Shaped Growth: Forecasting adoption rates of alternative solutions

Path Dependency: Understanding how past decisions constrain future options

Emergent Properties: Anticipating new behaviors from system interactions

4. Case Studies and Analysis

4.1 Red Sea Crisis: Geopolitical Disruption

Houthi attacks in the Red Sea created severe shipping disruptions.

Layer 1 (Data): Vessel tracking revealed 278% lower Suez Canal traffic compared to the Ever Given incident. Satellite-connected devices provided continuous location data, with occasional security-related communication blackouts.

Layer 2 (Capabilities): The crisis triggered adaptive routing of 606 vessels around the Cape of Good Hope. Organizations deployed enhanced security protocols, dynamic capacity management, and collaborative coordination mechanisms.

Layer 3 (Patterns): Reinforcing feedback loops emerged where security threats trigger vessel rerouting, which increases operational costs, leading to further rerouting decisions that amplify economic impacts across the network. 3-phase temporal pattern identified: Initial shock (weeks 1-2), Adaptive response (weeks 3-8), New equilibrium (weeks 9+). Critical security incident frequency above 2 per week triggered mass rerouting decisions.

Layer 4 (Prediction): Future maritime chokepoint disruptions will trigger route equilibrium before stabilizing in cycles. Alternative routing will follow S-curves from initial adoption to peak usage. Initial route avoidance will overshoot optimal levels before correcting, while existing carrier relationships will delay adaptation. Emergent carrier-insurer information networks and dynamic security protocols will create new collaborative resilience mechanisms.

4.2. Panama Canal Drought: Environmental Constraint

Layer 1: AIS tracking enabled monitoring of vessel movements, draft levels, and alternative routing. Integration with meteorological data enhanced strategic decision-making.

Layer 2: Dynamic capacity management manifested through cargo load adjustments, modified vessel scheduling, and coordinated slot allocation between canal authorities and shipping companies.

Layer 3: Critical water level thresholds were identified below which operational capacity decreased non-linearly. The crisis exhibited distinct temporal patterns as water levels gradually decreased over months. Lower water levels reduce operational capacity, concentrating traffic on remaining viable routes, further straining system performance.

Layer 4: Future environmental infrastructure constraints will trigger throughput optimization, with capacity oscillating in seasonal patterns. Alternative routes will follow S-curves from peak usage, stabilizing at permanent levels. Initial restrictions will overshoot optimal levels before adjusting, while shipping contracts will delay adaptation. Dynamic capacity allocation systems and environmental monitoring integration will create adaptive infrastructure management capabilities.

4.3 COVID-19 Outbreak in China

Layer 1: Real-time visibility revealed vessel congestion around major Chinese ports (Shenzhen, Ningbo, Shanghai), decreased

container loading activities, and manufacturing facility operational status.

Layer 2: Despite lockdowns, some facilities maintained operations through adaptive measures. Yantian port sustained partial operations, while manufacturers like Foxconn implemented "closed circuit" production systems.

Layer 3: COVID-19 outbreaks trigger lockdown measures, which reduce manufacturing capacity, leading to port congestion that creates global supply chain impacts in a reinforcing cycle. Lockdown measures suppress case numbers, enabling manufacturing operations to gradually resume, reducing port congestion and restoring normal supply chain flows. Manufacturing capacity below 30% triggered widespread global supply chain alerts. 2-week delay between lockdown implementation and manufacturing impact, 4-week delay for port congestion effects.

Layer 4: Future health disruptions will trigger minimum viable production disruption cycles followed by recovery phases. Adaptive manufacturing will follow S-curves. Initial shutdowns will overshoot optimal levels before adjusting, while existing supplier networks will constrain diversification. Hybrid automated-human systems and health monitoring integration will create adaptive production capabilities.

4.4 Baltimore Bridge Collapse: Infrastructure Failure

Layer 1: Container tracking enabled immediate assessment of affected cargo and alternative routing options. Data revealed cargo redistribution to New York (41%), Norfolk (30%), and Newark-Elizabeth (10%).

Layer 2: Rapid response protocols, adaptive routing capabilities, and multi-modal coordination demonstrated resilience through dynamic capability deployment.

Layer 3: System progressed through Stability (normal port operations) to Disruption (bridge collapse) to Rapid Reorganization (cargo redistribution) to New Stability with altered port utilization patterns. Port closure forces cargo redistribution, which increases capacity strain at alternative ports, creating temporary bottlenecks that gradually resolve through system adaptation. Immediate disruption followed by exponential recovery curve over 8-12 weeks. Port closure above 72 hours triggered permanent routing changes.

Layer 4: future infrastructure failures will trigger regional capacity redistribution within 72-96 hours, with exponential recovery interrupted by temporary oscillations. Multi-modal solutions will follow S-curves from 20% initial adoption to 90% peak usage, stabilizing at 35-45% integration.

Initial redistribution will overshoot sustainable capacity by 15-30% before adjusting to 80-90% utilization, while terminal contracts will delay optimization by 4-6 weeks. Regional port cooperation networks and integrated multi-modal platforms will create collaborative infrastructure resilience capabilities.

4.5 Israel-Iran Conflict: Geopolitical Tensions

Layer 1: Vessel transit monitoring, security incident reporting, and insurance premium tracking provided strategic intelligence about escalating risks.

Layer 2: Enhanced risk assessment frameworks, detailed contingency planning, and strategic inventory positioning demonstrated adaptive capabilities.

Layer 3: Historical routing decisions create constraints on rapid adaptation, where established routes influence current choices, limiting flexibility during crisis escalation. Incident patterns influence risk assessment, which affects routing decisions, creating feedback that either amplifies or dampens route avoidance behaviors.

Layer 4: Future geopolitical tensions will trigger risk-cost optimization, with route decisions oscillating according to security incident patterns. Regional avoidance will follow S-curves from cautious response to peak avoidance, stabilizing at risk mitigation levels. Initial assessments will overshoot optimal measures before adjusting, while existing service agreements will constrain adaptation. Real-time dynamic insurance pricing and integrated security intelligence algorithms will create adaptive risk management capabilities extending beyond specific conflict zones.

5. Implications

The RTAR model advances theory in three key ways:

1. **Enhanced Resource-Based View:** Real-time data serves as a strategic resource with unique temporal qualities that enable resilience capabilities, extending traditional RBV [16].
2. **Complexity Science Integration:** Identifies patterns like cascading effects, feedback loops, and threshold effects across diverse disruptions, supporting [28] conceptualization of supply chains as complex adaptive systems.
3. **Systems Dynamics Application:** Provides empirical validation of systems dynamics concepts in supply chain contexts, addressing [29] call for research that connects theory to practice.

For supply chain practitioners, our findings suggest four critical strategies:

1. **Strategic Visibility Investment:** Integrate diverse visibility technologies (AIS tracking, IoT devices, satellite imagery, policy monitoring) into a unified ecosystem.
2. **Pattern-Based Early Warning Systems:** Develop systems that monitor known disruption patterns, track threshold indicators, and detect emerging cascading effects.
3. **Adaptive Governance Structures:** Distribute decision-making authority, establish escalation protocols, and create formal mechanisms for sharing visibility data across organizational boundaries.
4. **Balanced Resilience Portfolio:** Invest in capabilities that address diverse disruption types rather than focusing exclusively on the most recent or high-profile events.

While providing valuable insights, this research has limitations including case selection constraints, potential perspective bias from relying primarily on Project44 manager interviews, and limited temporal scope. Future research should investigate comparative effectiveness of different visibility technologies, integration with sustainability objectives, and network-level resilience dynamics.

In conclusion, real-time visibility serves as a catalyst for adaptive resilience by enabling organizations to detect patterns, predict system behavior, and implement effective adaptive strategies across multiple disruption contexts. The RTAR model provides a comprehensive framework for understanding and enhancing supply chain resilience in an increasingly volatile global landscape.

6. Conclusions

This research addresses how real-time visibility facilitates adaptive resilience in global supply chains through analysis of five major disruptions spanning geopolitical, environmental, health, and infrastructure challenges. The RTAR model provides a comprehensive four-layer framework explaining how organizations transform real-time data into strategic capabilities, revealing three critical mechanisms: information velocity, system-wide transparency, and predictive capability that collectively enable proactive crisis management. Our findings demonstrate that while specific disruptions require context-dependent responses, underlying resilience mechanisms exhibit common patterns including cascading effects, feedback loops, and threshold effects across diverse disruption types, suggesting organizations can develop generalizable

capabilities through strategic visibility investments.

The RTAR model contributes to supply chain management theory by integrating Resource-Based View, Dynamic Capabilities, and Systems Dynamics perspectives while providing practical guidance for building adaptive capabilities in an increasingly volatile global landscape. Future research should investigate comparative effectiveness of visibility technologies, network-level resilience dynamics, and integration with sustainability objectives. Real-time visibility serves as a catalyst for adaptive resilience by enabling organizations to detect patterns, predict system behavior, and implement effective adaptive strategies across multiple disruption contexts, providing a comprehensive framework for understanding and enhancing supply chain resilience.

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