

Topological characteristics, formation mechanisms and risk propagation simulation of global unmanned aerial vehicle industrial chain trade network

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Abstract: As a strategic high-tech product, the application of unmanned aerial vehicle (UAV) has exerted a profound impact on military and civil domains, becoming a new focal point of major-power technological competition. Currently, global UAV trade is deeply embedded within intricate international geopolitical dynamics, rendering it vulnerable to multiple risk shocks. To address these challenges, an analytical framework of “pattern-mechanism-risk” is constructed. By employing complex network analysis, exponential random graph model (ERGM), and cascading failure model, this study dissects the topological characteristics and formation mechanisms of the global UAV industrial chain trade network in 2023. Furthermore, it simulates the propagation processes of risks triggered by upstream supply reduction. Results indicate that (1) The upstream, midstream, and downstream trade networks display structural characteristics spanning multipolarity, regionality, with the mainland of China playing a core exporting role across all segments. In the downstream segment, the trade community led by the mainland of China encompasses more than 85% of global economies and accounts for over 60% of the total trade value. (2) Endogenous structural and exogenous factors jointly shape the architecture of the trade network. Synergy effects across various industrial chain segments, particularly the midstream segment, play a prominent role in driving network formation. (3) Risk propagation within the industrial chain manifests a minority impact phenomenon. Basic material supply reduction in the mainland of China will impact over 90% of economies, including Germany and the United States, whereas the disruptive scope of the United States remains contained within the Americas. This study provides valuable references for the effective formulation of UAV industrial chain security policies and the scientific governance policies of dual-use technology products.

Keywords: Unmanned aerial vehicle; Industrial chain trade; Complex network analysis; Exponential random graph model; Risk simulation; Cascading failure model

1. Introduction

Emerging from the profound integration of next-generation electronic information technology and the aviation industry, unmanned aerial vehicle (UAV) is widely recognized as one of the most disruptive and transformative strategic high-tech products today (Fox, 2020). Characterised by technological features such as autonomy, intelligence, and maneuverability (Mannan et al., 2025), UAV transcends the spatial limitations of traditional socio-economic activities, driving the expansion of diverse civilian sectors—including agriculture (Wanyama et al., 2024), logistics (Zhao et al., 2025a), and topographic mapping (Zhang et al., 2021)—into low-altitude airspace, catalysing new economic paradigms, notably the low-altitude economy (Liao et al., 2024). In recent years, major economies including China (The State Council of the People’s Republic of China, 2021), the United States (United States Congress, 2021), and the European Union (European Commission, 2022) have successively promulgated targeted policies and regulations for the UAV industry, significantly propelling the development of the low-altitude economy. As of 2024, the global UAV

market, encompassing both military and civilian applications, had surpassed \$83 billion in scale. It is projected to maintain a compound annual growth rate of 9.3%, reaching \$182.4 billion by 2033 (Grand View Research, 2026). Simultaneously, in recent geopolitical conflicts such as the Russia-Ukraine and Middle East conflicts, UAV has facilitated novel asymmetric warfare tactics, including “precision strikes,” “loitering munition attacks,” and “space-based satellite interconnections,” thereby cementing their status as an important weapon dictating the trajectory of modern warfare (Su, 2025). However, modifying civilian UAV into weaponry has caused frequent misuse and severe civilian harm, with over 3,000 casualties in the Russia-Ukraine conflict alone (United Nations, 2026). Consequently, development opportunities in the UAV industry coexist with the governance challenges of dual-use technologies. Looking forward, against the contemporary backdrop of balancing development and security, pursuing a dynamic equilibrium between “stimulating industrial vitality” and “enforcing security controls” has emerged as a crucial issue for governments worldwide in the scientific governance of dual-use technology products.

The production process of UAV spans materials, R&D, and assembly, creating a geographically dispersed yet technologically intertwined global division of labor. In 2026, the global UAV industry encompasses 1,413 enterprises across over 70 economies (Drone Industry Insights, 2026). However, unilateral policy interventions (Wang, 2026), manufacturing reshoring (Gur and Dilek, 2023), trade frictions (Ju et al., 2024), and geopolitical conflicts (Liu et al., 2023a) are disrupting the global division of labor within the UAV industrial chain, substantially heightening the risk of industrial chain disruptions. For instance, China’s export controls on military-grade complete products have triggered pronounced volatility in global trade value (Zhang et al., 2025). Concurrently, the United States and the European Union have tightened restrictions on upstream raw materials and midstream components (The White House, 2025; European Commission, 2026). This shift indicates that the dimension of competition is expanding from complete product toward the midstream and upstream segments of the industrial chain. Against the backdrop of highly interconnected global UAV technology, export restrictions on basic materials could trigger vertical, cross-segment risk propagation through trade linkages, ultimately impeding the global manufacturing of UAV complete product (Miao et al., 2024). Therefore, acquiring a comprehensive understanding of the global trade pattern of the UAV industrial chain and scientifically assessing the cascading impact of disruption risks will facilitate the formulation of targeted industrial chain security policies and informing the governance of dual-use technology products.

The globalized division of labor in the UAV industry creates intricate trade linkages across industrial chain segments. Complex network analysis provides a unique perspective for exploring these multifaceted relationships (Barigozzi et al., 2011). In terms of research objects, existing studies have employed this method to quantitatively delineate the evolutionary characteristics of

trade networks for various products, with the empirical focus progressively expanding from traditional commodities, such as agricultural products (Cao and Lei, 2025) and critical minerals (Chen et al., 2024), to emerging high-tech commodities, including industrial robots (Chen et al., 2025), semiconductors (Ren et al., 2023), photolithography equipment (Peng et al., 2026), and wind power equipment (Wu et al., 2026). In terms of research content, by examining small-world phenomenon, core-periphery structure, and trade community structure, researchers have characterised the evolution of economies' positions in specific product trade networks (Zhang et al., 2022; Chen et al., 2025). Building upon the construction of trade networks, methods such as indicator evaluation method (Lu et al., 2025), gravity model (Yang et al., 2026), and Quadratic Assignment Procedure (QAP) model (Liu et al., 2023b) are commonly employed to explore the influencing factors of trade networks. However, these traditional methods focus solely on exogenous variables, neglecting the self-organisation and endogenous processes inherent in network formation. Exponential random graph model (ERGM) addresses this by integrating both endogenous and exogenous variables (Cai et al., 2026), enabling the “bottom-up” and “holistic internal-external” analysis of network formation across food (Cao and Lei, 2025), minerals (Zhao et al., 2025b), and high-tech products (Ou et al., 2024). Amid the growing frequency of “black swan” events, identifying potential trade risks has become a crucial prerequisite for maintaining the stability of industrial and supply chains. Cascading failure model can effectively simulate the dynamic propagation of risks across product trade networks within different segments of the industrial chain (Zheng et al., 2025). Applying this approach to high-tech commodities—such as lithium-ion batteries (Hu et al., 2021), cobalt (Liu et al., 2024), wind turbines (Zhao et al., 2023), and photovoltaic materials (Miao et al., 2024)—allows researchers to evaluate both direct and indirect impacts of supply disruptions from specific economies.

Currently, research on UAV primarily focuses on R&D (Emimi et al., 2023; Hafeez et al., 2023), regulations (Nelson and Gorichanaz, 2019; Dai et al., 2025), and practical applications (Tang et al., 2026). As for the UAV manufacturing process, researchers pay more attention to material selection (Baltić et al., 2024), system development (Hyun et al., 2024), and flight control simulation (Zhang et al., 2023). However, research on UAV as commodities in multilateral trade relations is limited to the perspective of complete product, primarily revealing the global trade pattern and the degree of impact of trade controls (Zhang et al., 2025; Ma et al., 2026). Existing research has not yet deeply analysed the trade flow characteristics of products across the upstream, midstream, and downstream segments of the UAV industrial chain. As the source of the entire industrial chain, fluctuations in the supply of basic material for UAV products will significantly affect the stability of the entire chain, yet current attention to this is similarly insufficient. Against the background of various economies attaching great importance to the security of the industrial and supply chains of high-

tech products, revealing the trade pattern of the UAV industrial chain and its potential risk is a prerequisite for maintaining its trade security and stability.

Based on this, this study aims to reveal the current trade patterns and potential risks of the global UAV industrial chain. Therefore, grounded in data availability, this study constructs the global UAV industrial chain trade network in 2023, attempts to analyse the topological characteristics and formation mechanisms of the trade network, and further simulates the propagation process of risks induced by the reduced supply of basic material in the upstream links of the industrial chain. This study aims to address the following questions: (1) How do trade patterns vary across industrial chain segments? (2) What are the formation mechanisms of the trade network? (3) What is the impact scope of cascading risks triggered by upstream supply reductions? By answering these three questions, this study aims to reveal the current trade pattern of the global UAV industrial chain and provide a scientific basis for responding to potential trade risks.

The major contributions of this study are as follows: (1) This study constructs an analytical framework of “pattern-mechanism-risk” for strategic high-tech product trade and conducts an empirical investigation focusing on the global UAV industrial chain trade network. (2) From an industrial chain perspective, this study identifies economies possessing trade competitive advantages in the UAV trade, revealing that trade dominance becomes increasingly concentrated as the UAV industrial chain extends downstream. (3) By dissecting the dominant driving factors underlying the trade network structural evolution across distinct segments of the UAV industrial chain through both endogenous and exogenous mechanisms perspectives, this study deepens scientific understanding regarding the formation mechanisms of strategic high-tech product trade networks. (4) Scenario simulations illuminate the propagation processes across industrial segments and the heterogeneity in impact scopes of supply risks originating from distinct risk-source nodes, such as the mainland of China and the United States, thereby further exploring scientific governance policies for strategic high-tech products.

The remainder of this paper is structured as follows. Section 2 details the data source and methods. Section 3 presents the analysis results. Section 4 provides the discussion, and Section 5 concludes the study.

2. Data and methods

2.1 Data source

Given the lack of a universally accepted international standard for classifying the UAV industrial chain, this study references industrial chain theory (Tan et al., 1999). Based on the process from raw material acquisition to final production, the UAV industrial chain is divided into three segments: Basic material, key component, and complete product. Representative products are respectively selected as the research objects for each segment. Based on data availability, this study

uses the import data of each segment's products in 2023 from the UN Comtrade as the trade data for the global UAV industrial chain. The trade data includes 203 economies (Supplementary Table S1). Upon verification, the import data for six economies—Russia, Belarus, Iran, Afghanistan, Iraq, and Bangladesh—was found to be missing. Therefore, the export trade value from other global economies to these economies was used for data supplementation. In accordance with the statistical caliber of the UN Comtrade, China's Hong Kong Special Administrative Region (China's Hong Kong SAR), China's Macao Special Administrative Region (China's Macao SAR), and Taiwan, Province of China, are respectively regarded as economies, and the mainland of China is also regarded as an economy for research. The composition and HS codes of the upstream, midstream, and downstream products are shown in Fig. 1. Data for the explanatory variables of the ERGM are sourced from databases including the World Bank, the Swiss Economic Institute, CEPII, GDELT, WIPO, and UN Comtrade (Table 1).

Table 1 Explanatory variables and data sources

Mechanism	Type	Variable	Data source
Endogenous	Endogenous structural effects	Edge (<i>Edges</i>)	Calculated by ERGM
		Reciprocity (<i>Mutual</i>)	Calculated by ERGM
Exogenous	Actor-relationship effects	Gross domestic product (<i>GDP</i>)	World Bank
		Medium and high-tech manufacturing value added (<i>Manu</i>)	World Bank
		KOF Globalisation index (<i>KOF</i>)	Swiss Economic Institute
		Worldwide governance indicators (<i>WGI</i>)	World Bank
		Patent cooperation treaty (<i>PCT</i>)	WIPO
	External network effects	Geographical distance network (<i>Distance</i>)	CEPII
		Linguistic proximity network (<i>Language</i>)	CEPII
		Geopolitical relations network (<i>Geopol</i>)	GDELT
		Basic material trade network (<i>Upstream</i>)	UN Comtrade
		Key component trade network (<i>Midstream</i>)	UN Comtrade
		Complete product trade network (<i>Downstream</i>)	UN Comtrade

Note: The variables for actor-relationship effects are logarithmically transformed. The matrix values of the geopolitical relations network are obtained by summing the daily data of the Goldstein Scale field in the GDELT database.

2.2 Methods

2.2.1 Complex network analysis

This study takes the economies participating in the global trade of the UAV industrial chain as nodes and the trade connections between economies as edges to construct the trade networks for the upstream, midstream, and downstream segments of the industrial chain (Wu et al., 2025). The trade network G for each segment is defined as:

$$G = (C, E, W, W') \quad (1)$$

Where: $C = \{C_1, C_2, \dots, C_n\}$ is the set of nodes, and n is the number of nodes. $E = \{E_1, E_2, \dots, E_m\}$ is the set of edges, and m is the number of edges. W and W' are the sets of all node attributes and all edge attributes, respectively. To avoid the impact of occasional, minor trade links on the macro

characteristics of global trade (Ou et al., 2024), this study excludes trade links in each segment of the industrial chain that are less than \$10,000. The total trade value after screening covers over 99.90%, which is highly representative.

2.2.2 Exponential random graph model (ERGM)

This study uses the UAV industrial chain trade network of each segment in 2023 as the dependent variable and employs ERGM to analyse the formation mechanisms of the trade network. The specific modelling algorithm is as follows (Ou et al., 2024):

$$P(G = X) = \left(\frac{1}{k} \right) \exp[\theta_1 \text{Edges} + \theta_2 \text{Mutual} + \theta_3 \text{Sender}(economy_i, economy_j) + \theta_4 \text{Receiver}(economy_i, economy_j) + \theta_5 \text{Edgescov}(N_{ij})] \quad (2)$$

Where $P(G=X)$ represents the probability of a random matrix X occurring in the UAV industrial chain trade network G , and $economy_i$ and $economy_j$ denote economies i and j , respectively. $1/k$ represents the normalization constant. θ denotes the vector of parameters to be estimated. *Edges* represents the edge statistics of the trade network, which is similar to the intercept term in traditional regression model. *Mutual* captures the reciprocity of trade relations. *Sender* and *Receiver* denote the export and import propensities of economies with specific attributes, respectively. *Edgescov* measures the impact of other relationships N between economies on the formation of trade links. Based on the constructed model, the Markov Chain Monte Carlo Maximum Likelihood Estimation (MCMC MLE) method is employed for parameter estimation. The t-statistic is used to assess parameter significance, requiring a p-value less than 0.1. The model's goodness of fit and selection are evaluated using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Finally, the model is implemented and tested using the “statnet” package in R.

2.2.3 Cascading failure model

This study defines the total import value of a node as its import capacity. The algorithm for risk cascade propagation is as follows (Miao et al., 2024) (Fig. 2):

(1) Initial shock: Assume that a specific event causes a reduction of α in the exports of node i .
 (2) Upstream propagation: If the import reduction of the affected node j exceeds its tolerance threshold β , node j will fail and become a new source of infection. Specifically, this failure occurs when the post-impact import value drops below $1-\beta$ times its original level. This process repeats in the upstream industrial chain trade network until no additional failed nodes emerge.

(3) Cross-segment propagation: Node i and the newly identified failed nodes from the upstream segment serve as the initial sources of infection for the midstream segment. Following the iterative propagation, supply reduction triggers successive node failures within the midstream and downstream trade networks. This process repeats until no additional nodes fail. The risk propagation process then concludes.

Both α and β are adjustable parameters, the network's overall impact depends on their ratio r of α to β , which tunes the criteria for node failure. An excessively high r causes any node failure to trigger large-scale cascading collapses, whereas an excessively low r prevents single-node failures from propagating systemically. As r increases, the maximum avalanche rate approaches a peak, defining this critical r value as the specific risk vulnerability index.

This study defines the number of failed economies from a risk source as the avalanche scale and its proportion to total economies as the avalanche rate, which is used to quantify the impact range of upstream risk sources.

3. Results

3.1 Topological characteristics of the UAV industrial chain trade network

3.1.1 Node attribute

The upstream segment exhibits a stable tripartite pattern led by the mainland of China, the United States, and Germany. Top five exporters by weighted out-degree (the mainland of China, the United States, Germany, Spain, and Turkey) account for 46.32% of the global total, while top five importers by weighted in-degree (Germany, the United States, France, the mainland of China, and the United Kingdom) represent 38.50%. Notably, major import and export markets highly overlap, with the mainland of China, the United States, and Germany ranking among the top five globally in both trade flows. This pattern stems from the nature of basic materials, such as aluminum alloys, titanium products, and carbon fiber, whose resource-intensive production is shaped by spatial resource constraints and high technological barriers. Consequently, highly industrialized economies (the mainland of China, the United States, Germany) leverage dual advantages in resources and processing technology to dominate the basic material network.

Trade dominance in the midstream segment is concentrated in East and Southeast Asian economies, including the mainland of China, Malaysia, and Taiwan, Province of China. The major exporting economies are the mainland of China, Taiwan, Province of China, the United States, Germany, and Japan, which collectively account for 56.17% of the global weighted out-degree. Meanwhile, top importers (the United States, Malaysia, Thailand, Germany, and the mainland of China) represent 42.97% of global weighted in-degree, with half of the top 20 trade-value economies originating from East and Southeast Asia. Leading positions held by the mainland of China, Malaysia, and Taiwan, Province of China underscore that technology-intensive key component trade is heavily Asian-dominated. The mainland of China and Taiwan, Province of China acting as key exporters and Malaysia as the second-largest importer. This concentration is primarily driven by the composition of midstream products, where electronic integrated circuits account for the majority share. Consequently, the trade pattern of UAV key component exhibits a high degree of similarity to that of semiconductors (Ou et al., 2024).

The downstream trade pattern exhibits a distinct unipolar pattern dominated by the mainland of China, whose export dominance is even more pronounced than upstream or midstream, accounting for 63.47% of global weighted out-degree. Malaysia, the United States, Turkey, and the Netherlands rank second to fifth, bringing the collective share of these top five economies to a striking 84.13% of global weighted out-degree. Top five importers (China's Hong Kong SAR, Ukraine, the US, the Netherlands, Germany) capture 60.69% of global import value. Notably, seven of the top ten trade links by trade value originate from the mainland of China, with their primary destinations encompassing the top five economies in import value. This pattern reflects its critical role in exporting complete product (a typical cluster-type product) via robust resource and industrial integration. Leveraging substantial midstream imports, Malaysia has integrated into downstream production to become the second-largest complete product exporter after the mainland of China, with its export link with the United States forming the second-largest global trade flow in 2023.

Across all UAV industrial chain segments, the mainland of China and the United States serve as critical global trade participating economies. Specifically, the mainland of China plays a vital exporting role, ranking first globally in export value across all segments with shares of 13.78%, 16.96%, and 63.47%, respectively. This trend demonstrates that the mainland of China's export dominance becomes increasingly pronounced as the industrial chain extends downstream. Conversely, the United States ranks among the global top five in both import and export values across all segments, deeply embedding itself in the global division of labor through active import processing and re-exporting. Overall, distinct product attributes generate technological disparities across segments, shaping a trade pattern from upstream multipolarity (a tripartite pattern) and midstream regionality (East and Southeast Asia dominance) to downstream unipolarity (the mainland of China's export concentration) (Fig. 3).

3.1.2 Network characteristic

From the perspective of network scale, the midstream segment records the highest number of nodes, edges, and weighted degree, followed by upstream, while downstream remains the smallest (Table 2). It reflects a distinct "olive-shaped" industrial chain trade pattern with an expanded middle and contracted ends. The key component trade network involves the widest range of economies, densest connections, and highest trade intensity, with 202 economies establishing 5,652 trade links totaling $\$167,719.35 \times 10^6$.

Table 2 Characteristics of the global UAV industrial chain trade network

Segment	Node	Edge	Weighted degree	Average path length	Average clustering coefficient
Upstream	172	3,984	53,740.86	2.062	0.655
Midstream	202	5,652	167,719.35	1.946	0.718
Downstream	108	970	10,332.92	2.346	0.428

Note: The unit of weighted degree is $\$1 \times 10^6$.

From the perspective of network connectivity, the trade networks across all segments of the

global UAV industrial chain exhibit a larger average clustering coefficient and a shorter average path length compared to random networks of equivalent scale. These topological features robustly conform to small-world phenomenon. Among them, midstream records the highest average clustering coefficient and shortest average path length, indicating that small-world phenomenon is most pronounced in key component trade. It shows that the midstream segment exhibits highest network connectivity and closest trading relationships.

3.1.3 Organisational structure

(1) Core-periphery structure

Overall, in 2023, the concentration coefficients of the trade networks across all segments of the global UAV industrial chain were above 0.85, indicating a clear core-periphery structure with significant differences between the core and peripheral nodes. Specifically, the core nodes of each segment are mostly composed of the top five exporting economies, demonstrating the significant control exerted by these major exporting economies in the global UAV industrial chain trade (Fig. 4).

Upstream, the UAV basic material network records the highest combined core and semi-core node proportion (9.30%) and lowest concentration coefficient (0.855), indicating dispersed dominance across economies. Specifically, the United States, Germany, and the mainland of China form the core layer as top three exporters, while the semi-core layer comprises 13 economies (e.g., Russia, South Korea, Japan, Canada).

Midstream, the UAV key component network exhibits intermediate structural metrics, with combined core and semi-core nodes at 4.95% and the concentration coefficient of 0.913. Specifically, the mainland of China, Japan, Germany, Taiwan, Province of China, and the United States constitute the core layer as the top five economies by export value, while South Korea, Mexico, Hungary, Singapore, and Italy comprise the semi-core layer. Notably, ten of the top eleven economies by export value occupy positions within the core and semi-core layers. Conversely, Malaysia and Thailand, despite ranking second and third in import value, are positioned only in the periphery layer. This structural asymmetry underscores an export-dominated pattern in key component trade.

Downstream, the UAV complete product network records the lowest core and semi-core node proportion (2.78%) and highest concentration coefficient (0.967), forming a distinct dual-core structure of the mainland of China and China's Hong Kong SAR. As the primary exporter accounting for over 60% of global exports, the mainland of China registers a commanding coreness of 0.775, reflecting its position as the absolute hub. Meanwhile, China's Hong Kong SAR occupies the core layer as the top global importer and sixth-largest exporter, playing a vital role in entrepot trade. Notably, against the backdrop of the Russia-Ukraine conflict, Ukraine emerged as a critical semi-core node after importing the world's second-largest value of complete product.

Overall, the core-periphery structure across UAV trade segments is intrinsically linked to

production models, transitioning downstream from resource-intensive to technology-intensive, and ultimately cluster-type configurations. Consequently, escalating R&D barriers concentrate trade dominance among a select few economies with comprehensive innovation capabilities. The mainland of China occupies a core position within the trade networks of all segments, with this dominance becoming most pronounced in the downstream segment. This multi-tier dominance is driven by domestic policy support for the low-altitude economy, robust technological R&D across the entire industrial chain, and strategic global market expansion, seamlessly empowering the mainland of China to exert a central, leading influence across the global trade network.

(2) Trade community structure

In 2023, the trade networks across all segments of the UAV industrial chain were consistently partitioned into four communities (Table 3).

Upstream, the overall sizes of these four communities remain relatively balanced. ① DEU-TUR Community incorporates 27.91% of global nodes, 75% of which are in Europe. It registers the highest intra-community trade value (31.76%) and connection (21.96%) shares, driven primarily by bilateral links among European economies like Germany, Switzerland, Italy, and the Netherlands. ② CHN-JPN Community encompasses the largest node share at 51.16% while accounting for 18.02% of global trade value, with 79.78% of its internal trade driven by four East Asian economies: The mainland of China, Japan, South Korea, and Taiwan, Province of China. ③ USA-CAN Community captures 11.63% of global nodes and 7.05% of global trade value, comprising North American economies (the United States, Canada, Mexico) alongside select Asian economies (e.g., Vietnam, Qatar). Notably, Vietnam emerges as a pivotal actor in cross-community trade by absorbing imports from the mainland of China, a link that ranks fifth globally in value, and exporting intensively to core members like the United States and Canada. ④ ESP-FRA Community is comparatively smaller, representing a modest 3.74% of global trade value across Western European and West African economies such as Spain, France, and Morocco.

Midstream, European-led communities have become increasingly prominent. ① DEU-ITA Community is the largest midstream trade community, capturing 41.09% of global nodes, 28.45% of edges, and 17.38% of trade value. The internal transactions concentrated among European partners (e.g., Germany, Italy, Hungary, Switzerland) that generating 90.54% of its intra-community trade. ② TWN-SGP Community captures only 6.44% of global nodes, primarily grouping East and Southeast Asian economies (e.g., Taiwan, Province of China, Singapore, Malaysia). However, its internal trade ranks second globally at 14.62%, driven by Taiwan, Province of China, which originates 62.95% of trade flows to the community partners. ③ USA-JPN Community spans multiple continents, encompassing 22.77% of global nodes and 10.28% of trade value, anchored by large-scale, bidirectional trade between the United States and partners like Mexico, Canada, and Japan. ④ CHN-KOR Community primarily assembles economies from Asia, Africa, and South

America, covering the second-largest node share at 29.70%. However, its internal trade intensity remains weak at just 3.99%, with flows originating from the mainland of China and South Korea toward other developing economies (e.g., India, Philippines, Argentina).

Downstream, global trade is primarily anchored by the trade community spearheaded by the mainland of China. ① CHN-NLD Community overwhelmingly dominates the downstream segment—capturing 85.19% of global nodes, 71.24% of edges, and 61.21% of trade value—encompassing critical economies such as the mainland of China, the Netherlands, China’s Hong Kong SAR, Germany, and Poland. Within this community, the mainland of China exerts a paramount export-leading influence, originating 79.48% of internal trade flows. These trade flows are directly channeled to top-ten global importers like China’s Hong Kong SAR, Germany, the Netherlands. ② MYS-USA, TUR-LVA, and THA-ARM Communities feature simpler structures of only five to six economies each, with respective trade value shares representing 9.68%, 5.57%, and 0.91% of the global total.

Cross-segment comparisons reveal that upstream and midstream trade communities are relatively balanced in size. In stark contrast, the downstream segment is dominated by the mainland of China-led global community encompassing most economies and trade activities. This divergence stems from upstream and midstream manufacturing dynamics, where production depends on resource acquisition and component processing. Europe and North America possess comparable basic material capacities, while East Asia leads in key component division of labor. Consequently, these segments have agglomerated into trade communities of a relatively uniform scale. Downstream, characterized by cluster-type products, the mainland of China’s formidable resource and industrial integration capabilities integrate economies lacking low-cost domestic import substitution into its community. Notably, this highly centralized structure dominated by a single economy harbors structural vulnerabilities, where upstream disruptions can rapidly trigger large-scale cascading impacts downstream.

Table 3 Trade community characteristics of the global UAV industrial chain trade network

Upstream						
Name	Intra-community trade		Node		Edge	
	Trade value	Percentage	Quantity	Percentage	Quantity	Percentage
DEU-TUR	17,069.40	31.76	48	27.91	875	21.96
CHN-JPN	9,681.52	18.02	88	51.16	809	20.31
USA-CAN	3,791.17	7.05	20	11.63	47	1.18
ESP-FRA	2,008.76	3.74	16	9.30	49	1.23
Total	53,740.86	/	172	/	3,984	/
Midstream						
Name	Intra-community trade		Node		Edge	
	Trade value	Percentage	Quantity	Percentage	Quantity	Percentage
DEU-ITA	29,142.57	17.38	83	41.09	1,608	28.45
TWN-SGP	24,515.31	14.62	13	6.44	59	1.04
USA-JPN	17,247.02	10.28	46	22.77	242	4.28
CHN-KOR	6,697.14	3.99	60	29.70	200	3.54
Total	167,719.35	/	202	/	5,652	/
Downstream						
Name	Intra-community trade		Node		Edge	
	Trade value	Percentage	Quantity	Percentage	Quantity	Percentage
CHN-NLD	6,325.25	61.21	92	85.19	691	71.24
MYS-USA	1,000.05	9.68	5	4.63	7	0.72
TUR-LVA	575.46	5.57	6	5.56	7	0.72
THA-ARM	83.93	0.81	5	4.63	4	0.41
Total	10,332.92	/	108	/	970	/

Note: Based on existing research (Zhang et al., 2022), the community's name is a combination of the names of the top two exporting economies within the community. In addition, the unit of trade value is $\$1 \times 10^6$, the unit of percentage is %.

3.2 Formation mechanisms of UAV industrial chain trade network

First, the benchmark models include only endogenous structural variables across Models 1, 4, 7 to capture the foundational effects of edges and reciprocity within each network segment. Second, Models 2, 5, 8 expand upon these benchmark models by incorporating node attribute variables. These characteristics span five critical socio-economic dimensions including economic development, manufacturing prowess, globalisation degree, governance level, and innovation capability. Finally, Models 3, 6, 9 introduce external network variables to fully account for relational drivers. This comprehensive specification evaluates the concurrent impacts of geographical distance, shared official language, geopolitical relationships, and industrial chain synergy effects (Table 4).

3.2.1 Empirical results of the model

(1) Endogenous structural effects

The coefficients for *edges* are all significantly negative, indicating that the UAV industrial chain trade network is not randomly formed, but rather driven by both endogenous and exogenous mechanisms such as network structure, node attributes, and external relations. The coefficients for *mutual* are all significantly positive and large, indicating a prominent mutual effect where two-way

trade accounts for 56.58%, 57.57%, and 39.38% across upstream, midstream, and downstream segments, respectively. This confirms that the effect of mutuality is most prominent in the midstream, further confirming that its trade links are the closest.

(2) Actor-relationship effects

The formation of trade linkages across the global UAV industrial chain is profoundly shaped by the intrinsic node attributes of individual economies. This network architecture exhibits a pronounced Matthew effect driven by economic development, manufacturing foundations, and degree of globalisation. Concurrently, institutional environments exert a distinct asymmetric influence on these linkages, whereas innovation capabilities introduce a compelling dual influence.

The estimated coefficients for *GDP*, *Manu*, *KOF* are consistently and significantly positive for both exporter and importer. This confirms a pervasive Matthew effect operating across all segments. Essentially, economies with advanced development, robust manufacturing, and high globalisation command superior competitiveness and R&D capabilities, significantly increasing their probability of establishing both import and export trade links. Germany serves as a classic case. Ranking in the global top ten for *GDP*, *Manu*, and *KOF*, it leverages immense scale, industrial depth, and market openness to secure top-ten import and export positions across the UAV industrial chain. This structural pattern is similar in global wind power equipment trade, highlighting a common phenomenon in high-tech manufacturing (Wu et al., 2026).

Regarding the quality of *WGI*, the Sender effects reveal that only the midstream segment exhibits a significantly positive coefficient, whereas the upstream and downstream segments fail to pass the statistical significance threshold. Conversely, the Receiver effects yield significantly positive coefficients across all UAV industrial chain segments. This reveals an asymmetric governance impact between import and export sides, driven by divergent supply and demand side mechanisms. On the export side, the research and development of key component is technology-intensive, requiring strict quality standards and rigorous certifications. Consequently, good institutional governance provides security and trust, serving as a vital catalyst for key component exports. In contrast, an economy's export competitiveness in upstream basic material and downstream complete product depends more heavily on manufacturing costs and the density of industrial communities than on institutional quality. This structural shift explains why the *WGI* Sender effects coefficients for these two segments lack statistical significance. On the import side, however, well-governed economies attract trade by enhancing policy stability and reducing transaction uncertainties, making them preferred destinations across the entire industrial chain.

Regarding the impact on *PCT*, the Sender effects show significantly positive coefficients in the upstream and midstream segments, whereas the downstream segment fails the significance test. Conversely, the Receiver effects yield significantly negative coefficients for both the upstream and midstream segments, with the downstream segment again failing the significance test. Collectively,

these patterns reveal a clear dual effect of export expansion and import substitution localized in upstream and midstream segments. On the export side, highly innovative economies with large patent value leverage technological edges and mature manufacturing systems to improve cost efficiency, thereby originating larger export value of basic material and key component. On the import side, advanced domestic R&D enables import substitution for essential UAV materials and components, reducing import dependence on foreign partners. Ultimately, this behaviour underscores a drive for technological sovereignty among leading economies in the UAV trade network. Taiwan, Province of China vividly illustrates this dynamic. As a leading patent holder, its export values rank tenth upstream and second midstream globally, whereas its imports fall outside the top twenty, highlighting a classic dual effect of export expansion and import substitution. Additionally, downstream complete products are cluster-type goods whose development relies on comprehensive industrial systems rather than general patents, explaining why downstream trade linkages remain unaffected by general innovation outputs.

In summary, across all network segments of the global UAV industrial chain, the formation of inbound and outbound trade linkages is positively driven by economic development, manufacturing prowess, and globalisation degrees. Conversely, institutional governance and innovation capabilities exert highly differentiated impacts depending on the specific segment. Economies characterised by good institutional governance consistently function as major destination markets by maintaining a prominent import presence across all segments. Furthermore, high innovation capacities actively propel economies to become leading exporters of upstream basic material and midstream key component. At the same time, this domestic technological superiority significantly reduces their reliance on foreign import links.

(3) External network effects

Empirical results demonstrate that linguistic proximity and inter-segment synergy effects jointly catalyse the formation of trade linkages across the global UAV industrial chain. Conversely, the constraining effects of geographical distance and geopolitical relationships appear relatively marginalized. Specifically, the estimated coefficients for the geographical distance network (*Distance*) are consistently and significantly negative across all models. However, the absolute value is remarkably small at just -0.0001. This statistical trace suggests that while geographical proximity does facilitate trade connections, its practical impact remains highly constrained. In contrast, the linguistic proximity network (*Language*) yields uniformly positive and significant coefficients. This outcome underscores that shared communication channels play an essential role in fostering global trade links. The geopolitical relations network (*Geopol*) fails to pass the statistical significance threshold in both the upstream and midstream segments. Yet, as the network transitions to the downstream segment, this coefficient turns significantly positive at 0.0001. This divergence stems from the product attributes at different segments. Upstream basic material and midstream key

component feature exceptionally versatile applications and high non-substitutability. Consequently, geopolitical frictions are currently insufficient to override such inelastic global demand. When downstream complete product carries sensitive dual-use attributes, the facilitating role of aligned geopolitical relations becomes apparent. Nevertheless, its actual magnitude remains marginal.

Internal trade activities within any specific segment of the industrial chain are significantly and positively cross-driven by the remaining two segments. Among these cross-segment dynamics, the midstream segment exerts the most prominent catalytic effect across the global UAV industrial chain trade network. Regarding upstream basic material trade, the estimated coefficients for the key component network (*Midstream*) and the complete product network (*Downstream*) are 0.1493 and 0.0584, respectively. This substantial variance demonstrates that midstream trade linkages provide a far stronger driving force. For midstream key component trade, the network segments of basic material (*Upstream*) and complete product (*Downstream*) yield coefficients of 0.1369 and 0.1340, respectively, with a difference of only 0.0029, indicating that the positive impact of upstream and downstream trade relations is relatively similar. Finally, concerning downstream complete product, the impacts of the basic material network (*Upstream*) and key component network (*Midstream*) generate coefficients of 0.0565 and 0.1689, respectively. These empirical findings confirm that the downstream segment is more influenced by midstream trade relations.

In summary, trade linkages across the global UAV industrial chain are primarily propelled by linguistic proximity and inter-segment connectivity. Sharing a common language drastically lowers communication barriers. By minimizing potential transaction frictions and cultivating mutual trust, linguistic alignment ultimately fosters highly resilient trade relationships. Furthermore, established trading links act as a catalyst for deeper cooperation across other parts of the network. This interdependency enables coordinated development and unlocks powerful synergy effects across the entire UAV industrial chain. Within this interconnected architecture, midstream key component trade plays a critical bridging role. Midstream expansion directly stimulates upstream basic material demand while accelerating downstream complete product trade, thereby driving linkages across all segments.

Conversely, the impacts of geographical distance and geopolitical relationships remain relatively constrained. This marginality is primarily driven by the technological monopolies and escalating global demand inherent to high-tech products under globalisation. Specifically, globalisation and technological advancements have eroded the frictional resistance of geographical distance on trade (Gong and Yin, 2017), while technological dependence cushions cost premiums induced by geopolitical volatility (Airaud et al., 2025). To safeguard supply chain stability in critical domains, certain economies absorb additional transaction costs from vast distances or political instability. Such risk tolerance fosters cross-continental linkages built on cultural trust and

inter-segment connectivity. These findings echo empirical insights on UAV complete product, and align with research on global semiconductor trade (Gu et al., 2024; Zhang et al., 2025).

Table 4 ERGM results of the global UAV industrial chain trade network

Variable	Upstream			Midstream			Downstream		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
<i>edges</i>	-3.0156***	-39.3871***	-28.0845***	-2.6193***	-44.3606***	-39.6289***	-4.2071***	-44.4892***	-23.3199***
<i>mutual</i>	3.2844***	1.3163***	0.6918***	2.9222***	0.7981***	0.4303***	3.7822***	1.2033***	0.7881***
<i>out_GDP</i>		0.5994***	0.4138***		0.6442***	0.5660***		0.5509***	0.1826**
<i>out_Manu</i>		0.5334***	0.2982***		0.4876***	0.3839***		0.4487***	-0.0066
<i>out_KOF</i>		1.2848***	0.7032***		1.2939***	0.9526***		2.0523***	1.3236**
<i>out_WGI</i>		-0.1238	-0.1993*		0.5509***	0.6930***		0.0216	-0.0225
<i>out_PCT</i>		0.0600***	0.1258***		0.0399**	0.0430**		0.0328	0.0712*
<i>in_GDP</i>		0.3755***	0.2642***		0.5576***	0.5354***		0.3419***	0.0922
<i>in_Manu</i>		0.2297***	0.0896**		0.2170***	0.1521***		0.3663***	0.1658*
<i>in_KOF</i>		0.8815***	0.9105***		0.2200*	0.0643		1.1817***	0.8227*
<i>in_WGI</i>		0.2634***	0.2445***		0.3205***	0.3200***		0.3805**	0.3423*
<i>in_PCT</i>		-0.0499***	-0.0214		-0.0412***	-0.0313*		-0.0489	-0.0421
<i>Distance</i>			-0.0002***			-0.0001***			-0.0001***
<i>Language</i>			0.4838***			0.4283***			0.4602***
<i>Geopol</i>			0.0001			0.0001			0.0001**
<i>Upstream</i>						0.1369***			0.0565***
<i>Midstream</i>			0.1493***						0.1689***
<i>Downstream</i>			0.0584***			0.1340***			
<i>AIC</i>	22,798.45	12,556.56	10,358.70	29,057.30	14,940.80	13,387.85	8,312.01	4,920.24	4,377.99
<i>BIC</i>	22,815.69	12,660.01	10,505.26	29,074.54	15,044.26	13,534.42	8,329.26	5,023.70	4,524.56

Note: *, **, and *** indicate significance at the 5%, 1%, and 0.1% statistical levels, respectively.

3.2.2 Goodness-of-fit test

Expanding upon the benchmark models, the comprehensive specifications integrate both node attribute variables and external network variables to evaluate the formation mechanisms across all network segments (Models 3, 6, 9). This integration successfully minimizes both the AIC and BIC. Such reductions indicate a superior goodness-of-fit for the comprehensive models. Furthermore, MCMC convergence diagnostic plots reveal that the parameter estimations exhibit stationary, random fluctuations centered around zero. These results show the high robustness and statistical reliability of the models (Fig. 5).

3.3 Simulation of risk propagation in the UAV industrial chain trade network

Risk simulation results reveal a rapidly decaying avalanche rate curve that shifts distinctly upper-rightward as the risk vulnerability index scales up (Fig. 6). This shifting trajectory indicates that under severe supply shocks, an expanding number of risk sources can disrupt neighboring nodes across the trade network. Specifically, upstream basic material supply reductions exert negligible impact at $r = 1$, whereas at $r = 2$, the maximum avalanche rate reaches 46.47%. At the critical

threshold of $r = 3$, a single dominant economy's supply contraction triggers a systemic failure affecting up to 91.29% of nodes, while the second-most influential economy disrupts nearly 60%. Beyond this point, as r continues to grow, supply failures across multiple economies trigger large-scale collapses, yet the maximum avalanche rate plateaus at 91.29%. Consequently, this study defines $r = 3$ as the risk vulnerability index, serving as the core parameter for subsequent scenario analyses.

3.3.1 Global propagation range

Risk simulation outputs reveal that basic material supply reductions exhibit sequential amplification along the UAV industrial chain. Specifically, an initial supply shock within the upstream segment propagates down the network. The average avalanche scale triggered by each upstream economy in the upstream, midstream, and downstream trade networks is 2.27, 3.63, and 3.95, respectively, with avalanche rates of 1.32%, 1.80%, and 3.66%. These results illustrate that when upstream exports reduce, the downstream network experiences the most severe disruptions by capturing the highest volume and proportion of node failures. The midstream segment registers the second-highest vulnerability. Strikingly, cross-segment repercussions on midstream and downstream trade far outweigh the localized damages contained within the upstream segment itself. It demonstrates that basic material shortages thus gather momentum as shock waves propagate sequentially across the global UAV industrial chain.

Node failures triggered by basic material supply reductions reveal a striking long-tail distribution across all segments (Fig. 7). This structure demonstrates that risk propagation within the global UAV industrial chain trade network is a minority-driven phenomenon. Within the upstream segment, a supply shock originating from the mainland of China triggers a catastrophic avalanche rate of 92.44%. This value completely dwarfs the disruptive scope of any other individual economy. In the midstream, vulnerability concentrates heavily around the mainland of China (86.14%) and Germany (85.64%). Downstream cascading collapse is dictated by five core economies: the mainland of China and Germany lead with 99.07%, followed by Taiwan, Province of China (90.74%), and Switzerland and Malaysia (89.81% each). Looking at the global influence across the entire UAV industrial chain, a reduction in basic material exports from the mainland of China inflicts the most severe systemic damage. This single shock paralyzes 91.29% of all economies in the trade network. Germany and Taiwan, Province of China yield disruptions of 58.71% and 22.41%, whereas the United States ranks sixth at just 14.73%. Overall, supply reductions among major exporters severely undermine trade stability, whereas shocks from non-major exporters exert limited impact.

3.3.2 Specific propagation path

The mainland of China, Germany, and the United States occupy the top three global positions in export values within the upstream segment of the UAV industrial chain. Recognizing their

systemic power, we designate these three core economies as the primary initial risk sources. This baseline setup enables a detailed simulation of the specific risk propagation paths across the global trade network under a targeted scenario of basic material supply reduction.

When the mainland of China serves as the initial risk source, a global avalanche erupts simultaneously across all three network segments, ensnaring 91.29% of economies, including Germany and the United States (Fig. 8). Upstream cascading failure propagates through six rounds, initially striking critical trading partners including Malaysia, Israel, Russia, and Ukraine. Subsequently, the risk spreads to advanced East and Southeast Asian economies, including Japan, South Korea, and Singapore, before permeating markets across Asia, Africa, and Latin America. The third and fifth rounds of propagation impacted the United States and Germany, respectively. Driven by this massive upstream disruption, inter-segment propagation infects adjacent segments, leaving the midstream highly vulnerable with an 86.14% node failure rate within two rounds. The downstream segment exhibits even lower resilience, suffering a near-total 99.07% node collapse after just one round of propagation.

When Germany serves as the initial risk source, the resulting avalanche progressively expands across network segments, ultimately hitting the United States and the mainland of China in the midstream and disrupting 58.71% of global economies (Fig. 9). Specifically, risk propagation within the upstream segment is highly contained, lasting for only a single round and merely impacting two economies, namely Switzerland and Luxembourg. However, the midstream experiences a far more prolonged disruption, spanning nine rounds with an 85.64% avalanche rate. The chronological sequence of this midstream contagion correlates closely with geographical proximity. The first three rounds affect top European key component importers (e.g., France, Italy) before expanding into Africa, the Americas, and Asia, reaching the United States in the sixth round and the mainland of China in the seventh. Conversely, the downstream segment suffers an immediate structural collapse, with one round failing 99.07% of nodes.

When the United States serves as the initial risk source, it induces a highly localized impact, yielding a 14.71% node failure rate confined to neighboring American economies and completely bypassing the mainland of China and Germany (Fig. 10). Upstream risk propagates through two rounds, primarily affecting North American partners (e.g., Canada, Mexico) with a low 9.88% avalanche rate. Similarly, midstream and downstream propagation hits adjacent American economies before radiating to a few isolated economies on other continents, yielding avalanche rates of 15.84% and 20.37%, respectively. Although the downstream contagion encompasses critical importers of complete product such as Japan and Italy, it fails to exert a significant shock on the mainland of China. This localized containment stems from structural properties: Over 30% of the United States exports concentrate in North America, leaving its upstream outputs un-embedded in

East and Southeast Asian midstream markets and preventing the upstream supply risks from escalating into a global crisis.

Comparing upstream supply risk paths across the three core economies reveals distinct patterns. As the dominant exporter, the mainland of China's basic material supply reduction impacts most economies through extensive trade linkages. Cascading rapidly via inter-segment propagation to destabilize midstream and downstream segments, this disruption exhibits a prominent "full-chain penetration" characteristic. In contrast, Germany's risk propagation does not spread deeply in the upstream segment. However, it triggers an "amplifying effect" through inter-segment propagation that primarily cripples global economies in the midstream and downstream segments. Conversely, the United States risk propagation exhibits a striking "proximity effect", remaining concentrated within neighboring American economies.

4. Discussion

4.1 Development prospects of the UAV industry

With high intelligence and maneuverability, UAV serve as a vital carrier for low-altitude resource utilization and economic expansion (Liao et al., 2024). This pivotal role has garnered substantial strategic attention from policymakers worldwide. In recent years, major economies including China (The State Council of the People's Republic of China, 2021), the United States (United States Congress, 2021), and the European Union (European Commission, 2022) have accelerated industry growth by delineating strategic objectives, establishing regulatory frameworks, and opening low-altitude airspace. These measures drive technological innovation and industrial upgrades to enhance global competitiveness. Regarding practical applications, UAV is widely deployed across developed and developing economies in agriculture, logistics, and mapping. This widespread adoption expands the low-altitude economy while delivering strong socioeconomic returns. From the perspective of the industrial chain, the UAV industrial chain encompasses multiple distinct segments such as raw materials, components, manufacturing, and operational services, possessing high value-creation potential (Zhou, 2024), with market scale projected to reach \$182.4 billion by 2033 (Grand View Research, 2026). However, the contemporary expansion of UAV industry faces severe institutional and operational bottlenecks, including trade regulations, lagging infrastructure, outdated legal frameworks, and a shortage of skilled personnel (Emimi et al., 2023). These problems collectively jeopardize the healthy trajectory of the industry. Conversely, addressing these challenges through standardized application scenarios, optimized policies, and reinforced technical training is crucial to enhancing sustainability and global competitiveness of the UAV industry.

4.2 Export control policies based on techno-nationalism may generate backlash risks

In recent years, to maintain high-tech dominance, certain economies have pursued techno-

nationalism through tariff hikes and export controls on high-tech products and raw materials. (Shen et al., 2024). However, within the global UAV industrial chain trade network, the disruptive efficacy of these unilateral export controls by certain economies remains remarkably constrained. For instance, the supply disruptions from the United States concentrate mainly within the Americas, failing to meaningfully impair manufacturing in the mainland of China. Conversely, the mainland of China ranks among the top three import sources of key component and complete product for the United States, accounting for 11.92% of midstream import and 32.08% of downstream import for the United States. Consequently, any reduction in basic material supply from the mainland of China immediately compromises the United States import security across the entire industrial chain. In other words, the strategy of the United States to monopolise upstream supply through unilateral technology controls fails to constrain the mainland of China. Furthermore, due to a profound structural dependence on Chinese suppliers across both the midstream and downstream segments, any escalation in bilateral competition may trigger severe backlash risks that jeopardize the domestic UAV industry of the United States.

4.3 The trend and prevention of weaponization of civilian UAV

Originally engineered for military use (Kozera, 2018), UAV has seen widespread civilian adoption in recent years, exponentially expanding the global market. However, it is worth noting that in modern wars such as the Russia-Ukraine and the Middle East conflict, a large number of low-cost civilian UAVs have been widely weaponized, shaping battlefield outcomes and causing over 3,000 civilian casualties in the Russia-Ukraine conflict alone (United Nations, 2026). Therefore, balancing industrial growth with international non-proliferation obligations, specifically restricting unauthorized militarization, is crucial for the industry's long-term stability. As a preeminent producer and exporter spanning every segment of the global UAV industrial chain, China published the "Catalogue of Dual-Use Items and Technologies Subject to Import and Export Licensing Administration" in 2025 (Ministry of Commerce of The People's Republic of China, 2025). This regulatory policy enforces precise export controls on complete product and key component that possess long range jamming or high-power strike capabilities. This proactive approach demonstrates China's responsibility as a major exporter while offering a solution for balancing development and security, serving as a reference for other major exporters to restrict the weaponization of civilian UAV.

4.4 Policy implications

To safeguard global UAV industrial chain stability and foster orderly industry growth, this study offers targeted policy recommendations for different categories of economies. (1) For import-dependent economies, they need to maintain existing trade partnerships while diversifying import sources. Concurrently, they should establish graded early-warning mechanisms to dynamically

respond to risk propagation, while accelerating domestic technological innovation to build resilience against supply shocks. (2) For export-oriented economies, on one hand, policymakers should recognize that blanket export controls across the entire UAV industrial chain frequently trigger self-inflicted backlash risks. On the other hand, the contemporary trend toward the weaponization of civilian platforms necessitates targeted regulatory interventions. Consequently, export-oriented economies should stringently monitor the export destinations of key component across both the upstream and midstream segments. Furthermore, mandating geofencing in downstream complete products, enforcing end-use compliance, and restricting unauthorized flight zones will allow exporting economies to mitigate illegal modifications from the perspective of the industrial chain.

5. Conclusion

This study constructs an analytical framework of “pattern-mechanism-risk” for strategic high-tech product trade and conducts an empirical investigation focusing on the UAV. By employing complex network analysis, ERGM, and cascading failure model, this study constructs the global UAV industrial chain trade network for 2023. On this structural foundation, it reveals the trade network topological characteristics of each segment, dissects the formation mechanisms, and simulates the dynamic propagation paths of trade risks triggered by the upstream basic material supply reduction. The results show that:

(1) The UAV industrial chain trade patterns of the upstream, midstream and downstream present a structural feature of “multipolarity-regionality-unipolarity”. Specifically, the global trade of basic material within the upstream segment exhibits a tripartite pattern dominated by the mainland of China, the United States, and Germany. In comparison, the structural governance of key component within the midstream segment becomes heavily concentrated within East Asian and Southeast Asian economies including the mainland of China, Malaysia, and Taiwan, Province of China. The global trade of complete product within the downstream segment shows a highly unipolar profile characterised by the unilateral export and global distribution of the mainland of China. The mainland of China commands the largest share of global exports across all segments of the UAV industrial chain and this dominant position expands progressively along the successive segments of the trade network. The key component trade network in the midstream segment involves the widest range of participating economies, the most prominent trade intensity, and the highest density of trade linkages, while the upstream segment ranks second and the downstream segment ranks last. As the industrial chain moves downstream, the core dominance of global trade becomes increasingly consolidated within a small number of economies led by the mainland of China. In the downstream segment, a global trade community jointly dominated by the mainland of China and the Netherlands, which encompasses over 85% of international economies and over 60% of total global trade value.

(2) The formation of the global UAV industrial chain trade network exhibits significant endogenous structural effects, actor-relationship effects, and external network effects. Specifically, reciprocity significantly fosters network formation across the upstream, midstream, and downstream segments of the industrial chain. Higher levels of economic development, manufacturing capacity, and globalisation actively encourage economies to establish more extensive import and export trade linkages across all segments. Economies with good institutional governance tend to act as prominent importers of products across the entire industrial chain. However, the level of institutional governance only exerts a positive effect on exports within the midstream segment. Stronger innovation capabilities drive economies to export within the upstream and midstream segments while simultaneously reducing their overall import dependence. Compared to the weak driving effects of geographical proximity and favorable geopolitical relations, linguistic proximity and inter-segment linkages exert a far more substantial impact on promoting trade relations within the UAV industrial chain. Among them, the synergy effects of the UAV industrial chain remain highly prominent, where trade activities within a segment drive other segments to form tightly connected trade linkages. This synergy effects manifest most significantly within the midstream segment.

(3) Trade risks triggered by an upstream basic material supply reduction expand their disruptive scope through tight trade linkages between industrial chain segments, ultimately exerting the most pronounced impact on the downstream segment. Concurrently, supply risks manifest a distinct minority impact phenomenon. Disruptions originating from a small number of major exporting economies, such as the mainland of China and Germany, severely destabilize the global UAV industrial chain trade network, whereas shocks emanating from other nodes remain relatively negligible. Specifically, when the mainland of China serves as the initial risk source, its propagation path exhibits a prominent “full-chain penetration” characteristic, dealing a substantial shock to 91.29% of global economies, including Germany and the United States. In contrast, Germany triggers an “amplifying effect” through intersegment risk propagation, which primarily cripples 58.71% of economies across the midstream and downstream segments, including the mainland of China and the United States. Conversely, risk propagation from the United States demonstrates a striking “proximity effect”. Its disruptive scope is heavily contained within adjacent American economies and fails to jeopardize the import security of the mainland of China and Germany.

Nevertheless, certain limitations need further investigation. (1) As an emerging product, UAV complete product was only incorporated into the UN Comtrade in 2022. Constrained by data availability, this study utilizes data from a single year, 2023. As more data become available, future research could further examine the long-term temporal evolution and driving mechanisms. (2) due to corporate strategies heavily reconfigure global trade patterns across industrial segments, future studies should refine the analytical scale to firm-level global production network (Yeung, 2022), to

deepen insights into industrial dynamics. (3) Given that exporters may face demand shortage risks from importer trade protectionism (Zhang et al., 2024), subsequent work should incorporate dual-sided supply and demand instabilities to map intersecting risk impacts on trade value, thereby providing scientific support for refined industrial chain and supply chain security solutions.

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Data availability

The data used in this study were obtained from various public databases, such as the UN Comtrade (<https://comtradeplus.un.org/TradeFlow>), the World Development Indicators Database (<https://databank.worldbank.org/source/world-development-indicators>), and the CEPII Database (https://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele.asp). All data processing has been fully described in the manuscript. If researchers need to use the processed dataset from this study, please contact the corresponding author to obtain it.

Author contributions

MH. L.: Writing - original draft, Formal analysis. C. Z.: Funding acquisition, Writing - review and editing. YM. W.: Conceptualization, Methodology. Q. Q.: Data curation, Methodology. SX H.: Formal analysis, Visualization. Y. X.: Formal analysis, Visualization. YZ Y.: Conceptualization, Methodology.

Competing interests

The authors declare no competing interests.

Figure legends

Fig. 1. Major products and HS codes across the UAV industrial chain. The figure focuses on UAV manufacturing, including upstream, midstream, and downstream. The numbers in brackets are the

corresponding HS codes.

Fig. 2. Cascading failure risk propagation process and specific algorithm. The cascading failure propagation process demonstrates how supply risks are transmitted from upstream to downstream. The specific algorithm shows the rules of risk propagation, where both α and β are adjustable parameters, the overall impact of the trade network depends on the ratio r ($r = \alpha/\beta$).

Fig. 3. Trade flows across distinct segments of the global UAV industrial chain. The chord diagram is drawn using the top 20 economies by trade value in 2023. The outer arc represents total trade value, the direction of the inner arc represents import and export trade flows, and the width of the arc represents the weighted in/out-degree.

Fig. 4. Core periphery structure of the global UAV industrial chain trade network. The size of the node is proportional to the coreness, and the width of the links connecting nodes represents the size of the trade flow.

Fig. 5. MCMC convergence diagnostic plots of partial variables in comprehensive model. The figure shows that the parameter estimations exhibit stationary, random fluctuations centered around zero, indicating that the model has high robustness and statistical reliability.

Fig. 6. Cumulative distribution of trade network avalanche rates triggered by upstream supply reduction. The ratio of failed economies to the total number of economies is defined as the avalanche rate. The initial risk source ranking is based on the magnitude of the avalanche rate.

Fig. 7. Supply risk propagation across distinct segments of the global UAV industrial chain. The figure illustrates the risk propagation when the risk vulnerability index $r = 3$.

Fig. 8. Supply risk propagation pathways originating from the mainland of China. The yellow circle represents the initial risk source, and purple circles represent the major affected economies with large trade value.

Fig. 9. Supply risk propagation pathways originating from Germany. The yellow circle represents the initial risk source, and purple circles represent the major affected economies with large trade value.

Fig. 10. Supply risk propagation pathways originating from the United States. The yellow circle represents the initial risk source, and purple circles represent the major affected economies with large trade value.

Upstream (Basic material)



Aluminum product
[760429]



Titanium product
[810890]



Carbon fiber
[681599]



Glass fiber
[701931]



Epoxide resin
[390730]



Midstream (Key component)



Electronic integrated circuit
[854290]



Radar apparatus
[852610]



Communication equipment
[851770]



Electric motor
[850131, 850132]



Rangefinder
[901510]



Propeller
[880710]



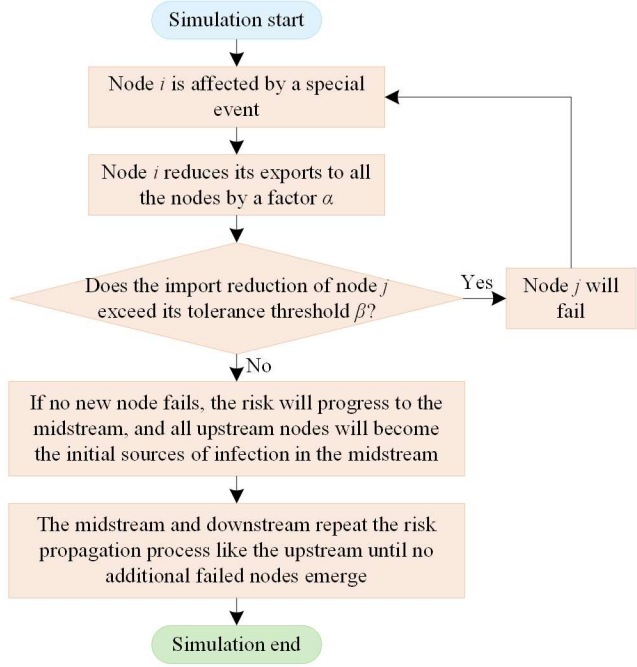
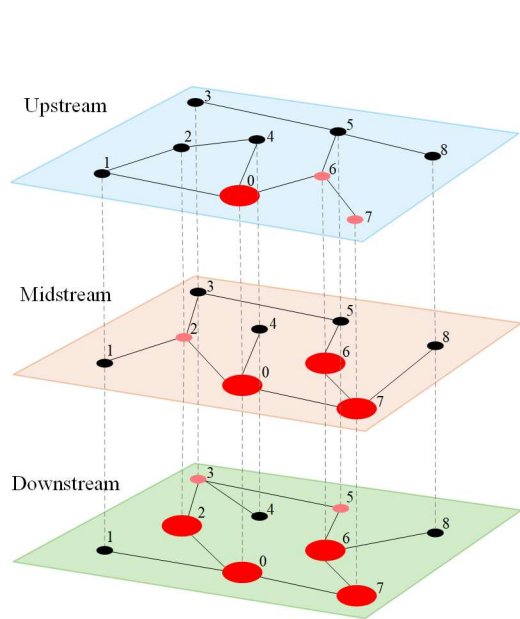
Mechanical appliance
[847990]



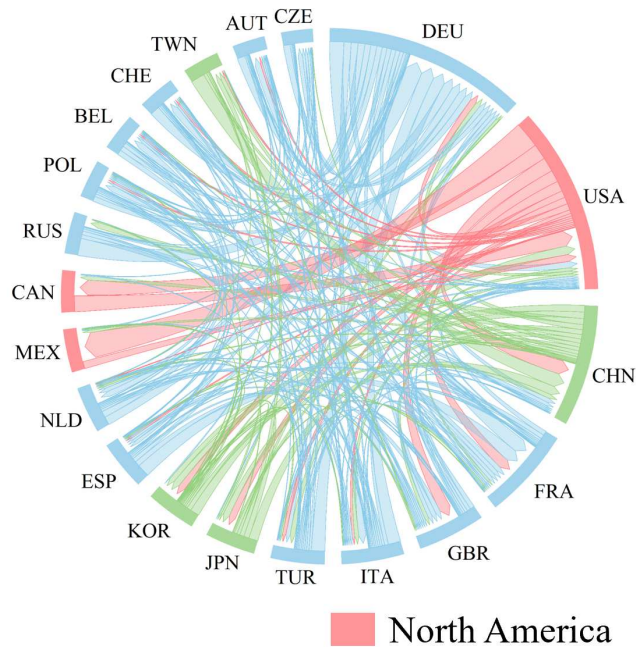
Downstream (Complete product)



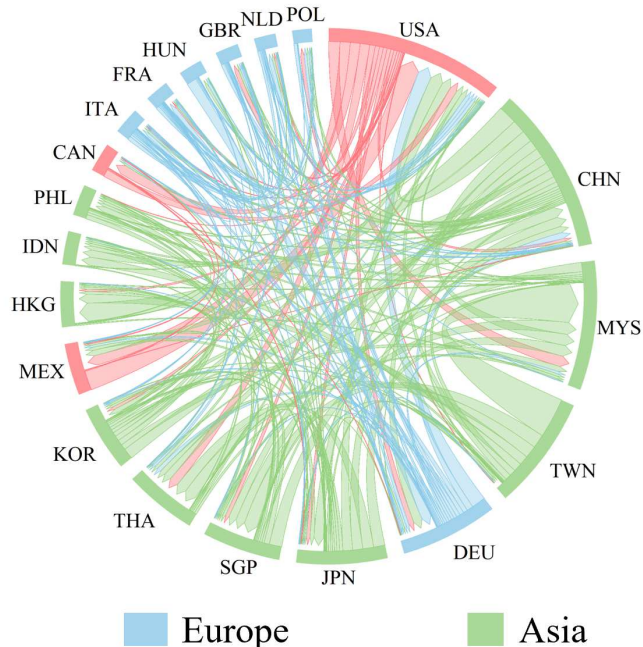
Unmanned aerial vehicle
[8806]



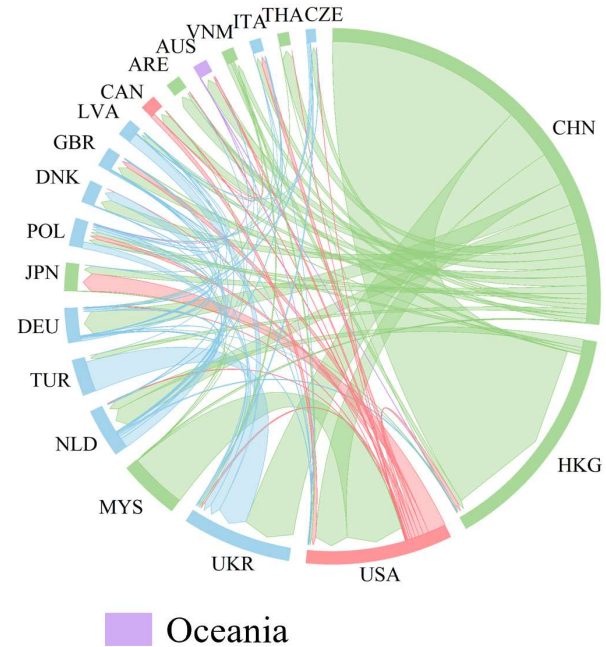
(a) Upstream



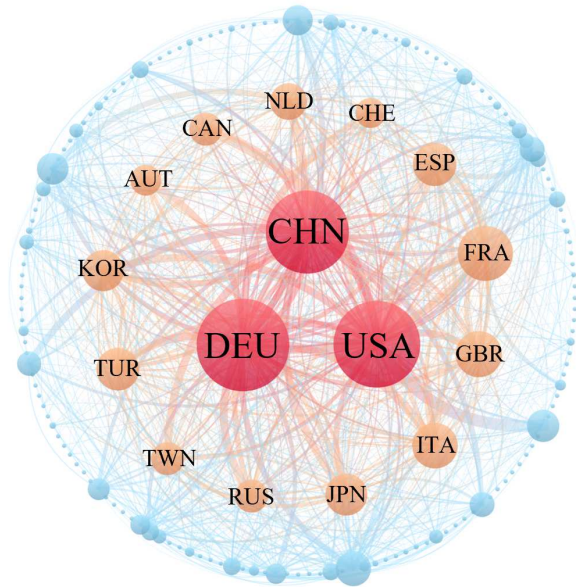
(b) Midstream



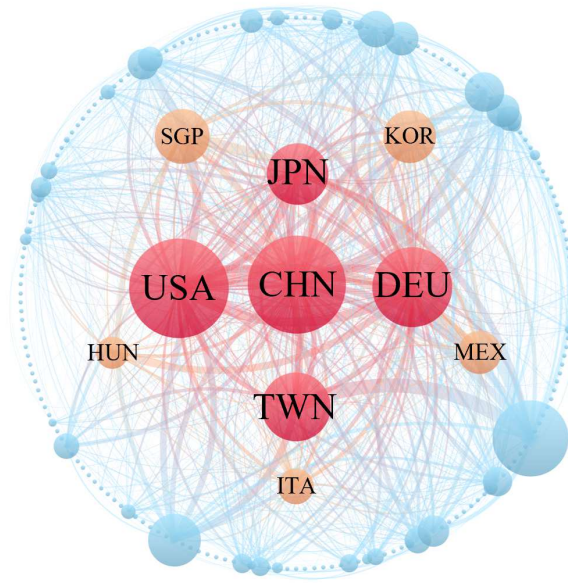
(c) Downstream



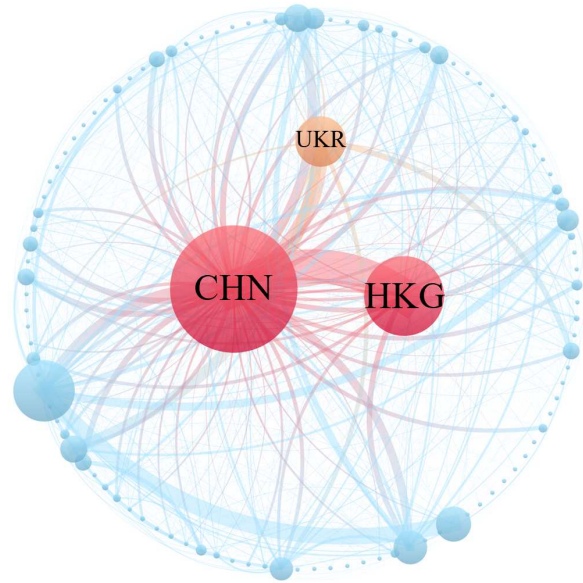
(a) Upstream



(b) Midstream



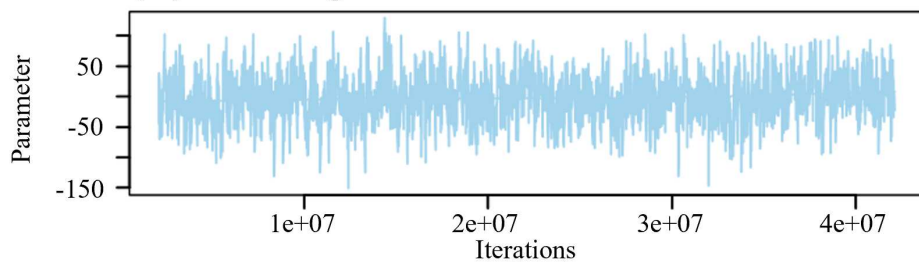
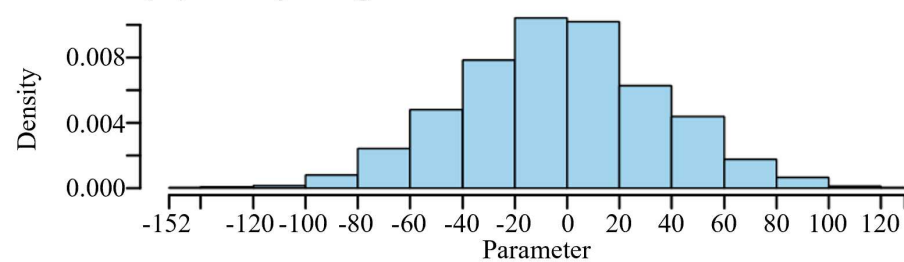
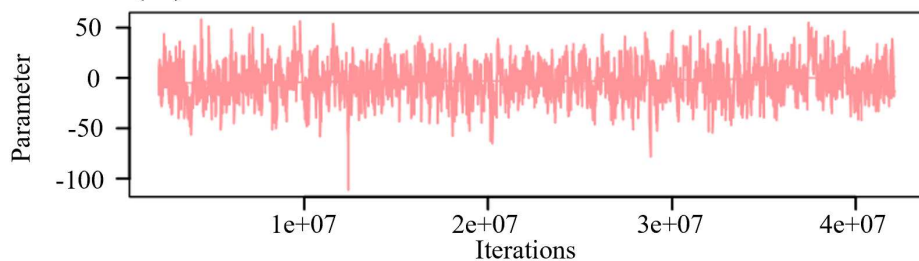
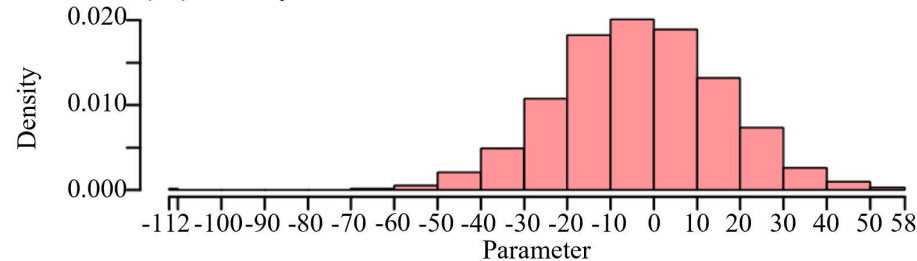
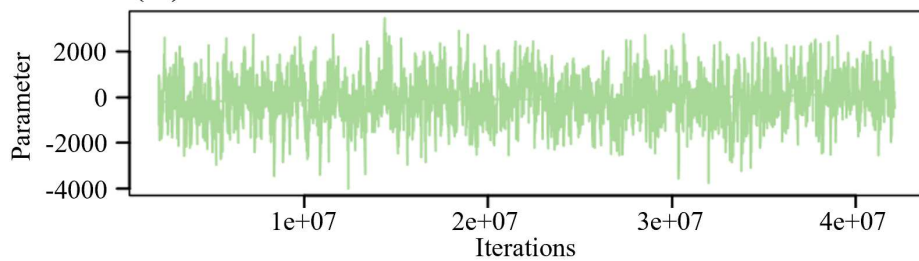
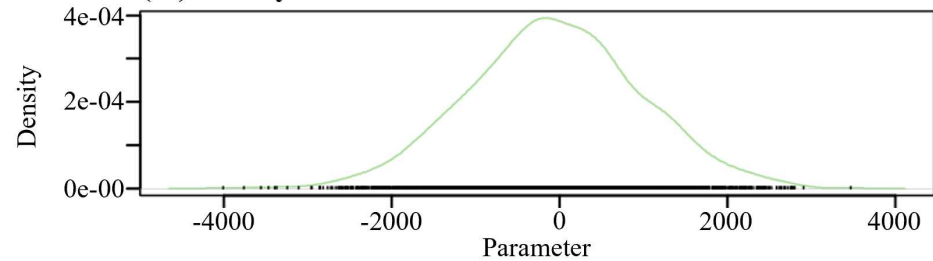
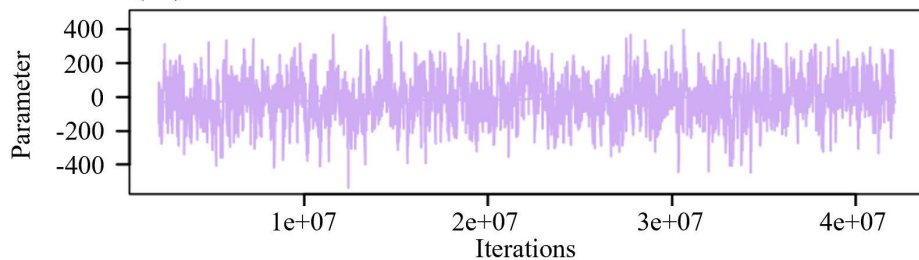
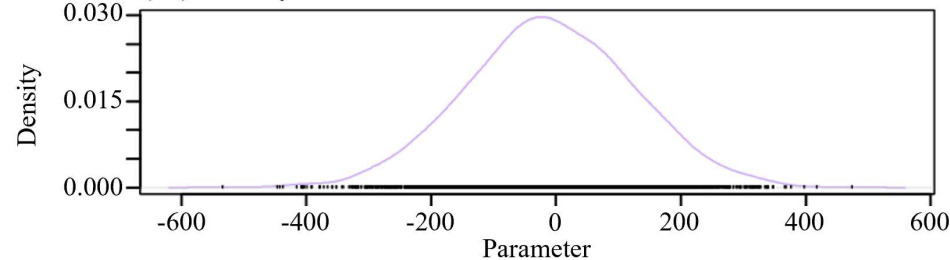
(c) Downstream

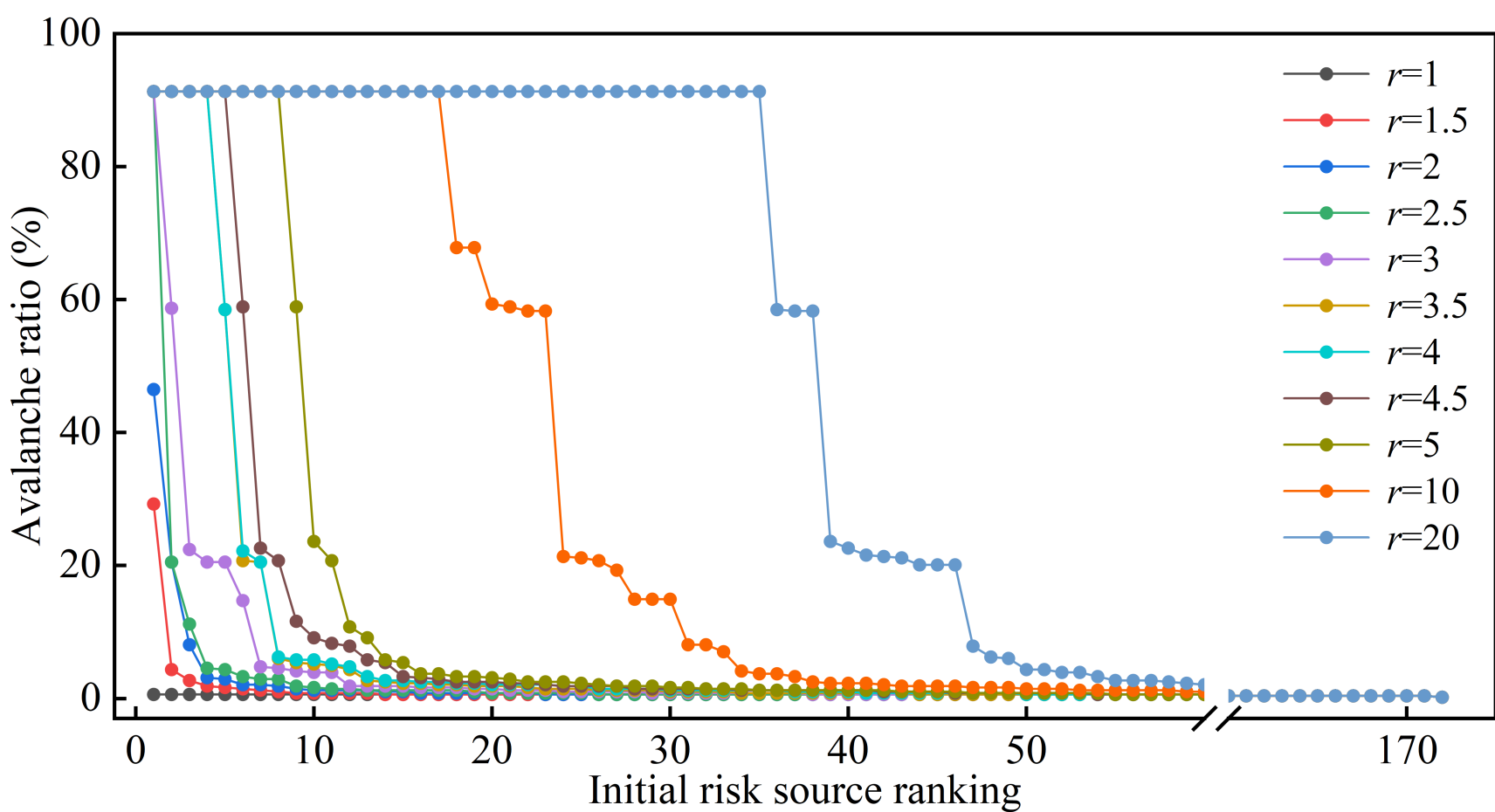


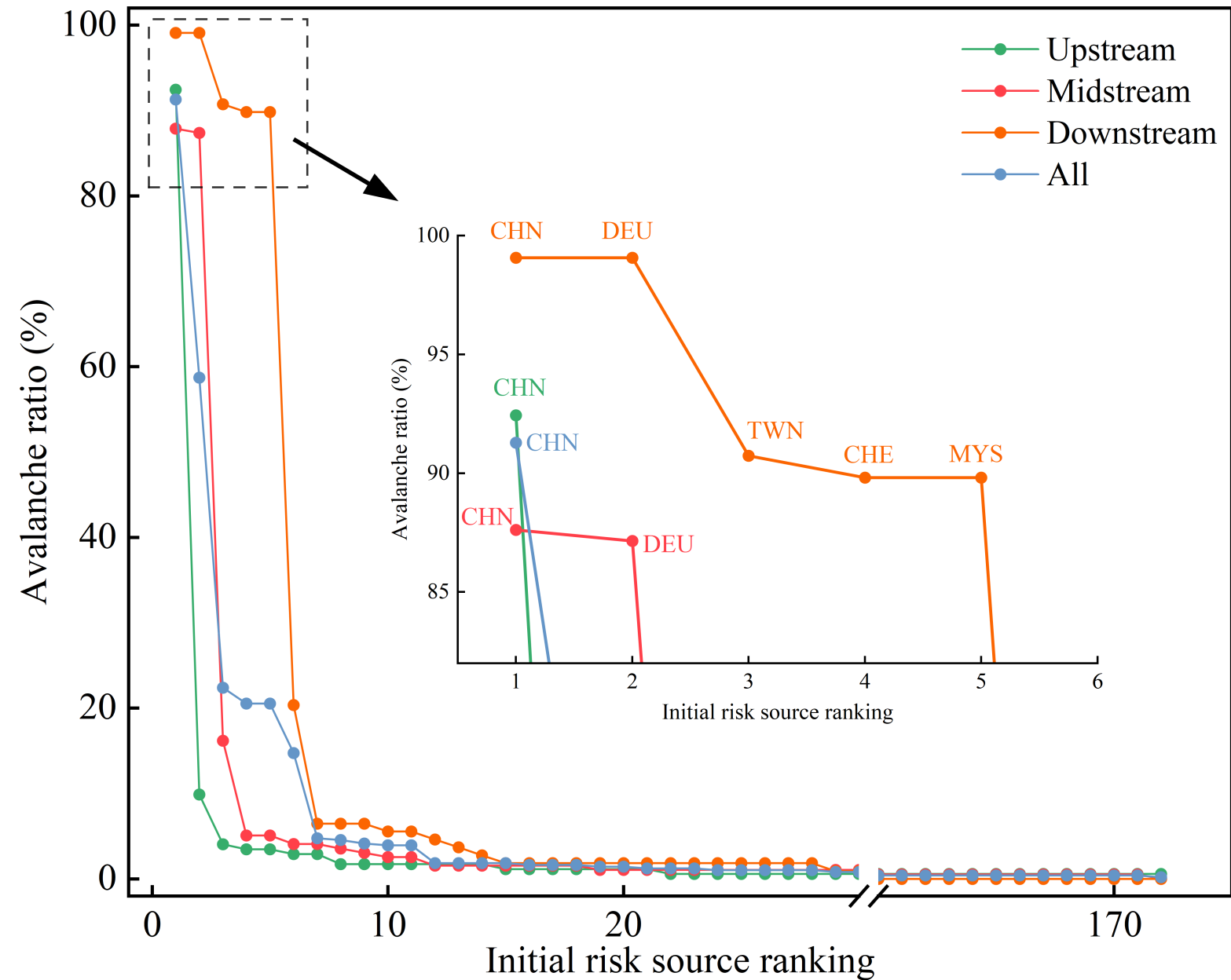
● Core

● Semi-core

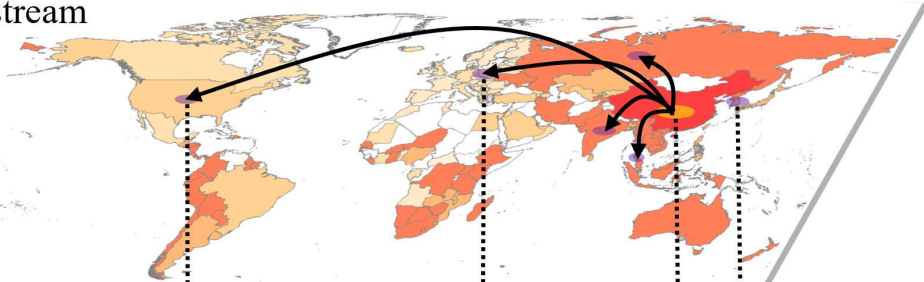
● Periphery

(a1) Trace of edges**(a2) Density of edges****(b1) Trace of *Mutual*****(b2) Density of *Mutual*****(c1) Trace of nodecov.GDP****(c2) Density of nodecov.GDP****(d1) Trace of nodecov.Manu****(d2) Density of nodecov.Manu**

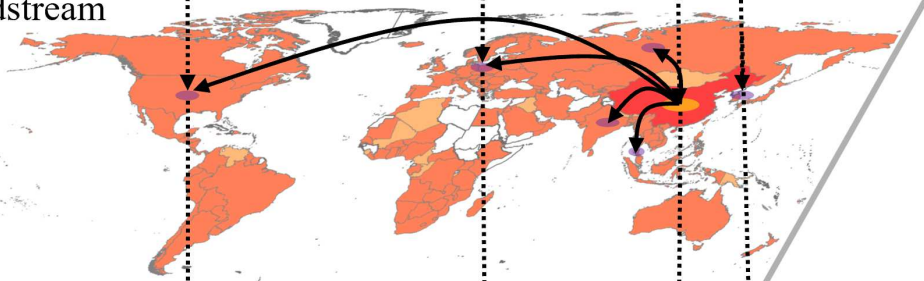




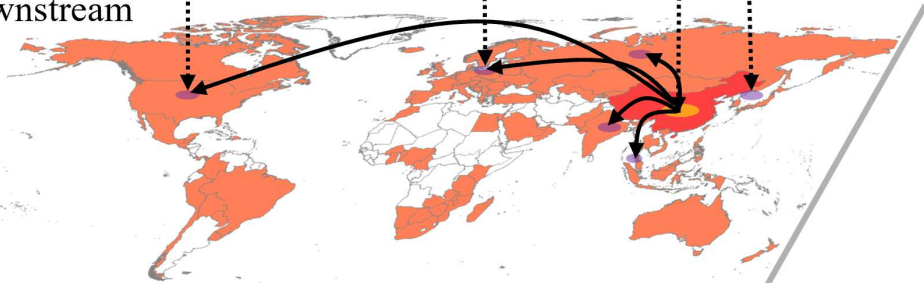
(a) Upstream



(b) Midstream



(c) Downstream



Round ■ 1 ■ 2 ■ 3 ■ 4 ■ 5 ■ 6

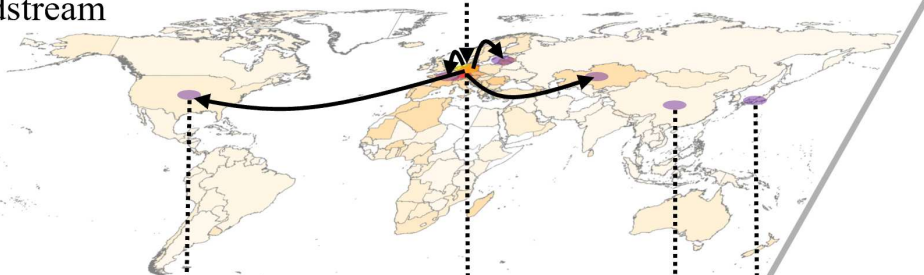
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→ Intra-segment transmission ⋯→ Inter-segment transmission

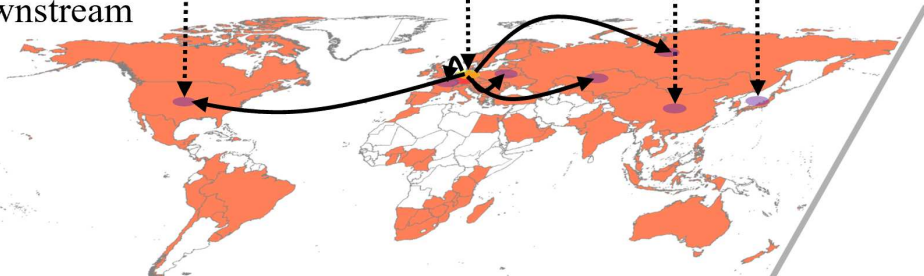
(a) Upstream



(b) Midstream



(c) Downstream



Round 1 2 3 4 5 6 7 8 9

□ No participation or influence

→ Intra-segment transmission ···→ Inter-segment transmission

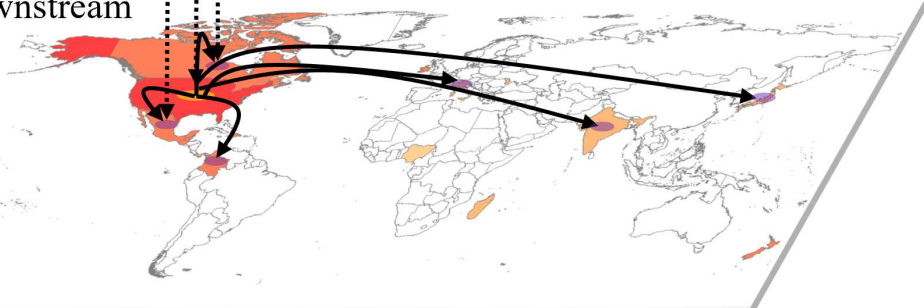
(a) Upstream



(b) Midstream



(c) Downstream



Round 1 2 3 4

□ No participation or influence

→ Intra-segment transmission ···→ Inter-segment transmission

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