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Bridging criticality assessment and supply chain resilience: a structured framework for operationalizing mitigation actions

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ABSTRACT

Critical raw materials underpin the energy transition, defense, and digitalization, yet criticality assessments remain diagnostic: they quantify supply risk and vulnerability without prescribing how to act. This gap is addressed through a structured review, from which 139 mitigation actions across mechanisms, capability types, and disruption pathway categories were compiled, harmonized, and classified. A dependency matrix encodes 278 relationships between actions. To operationalize the resulting catalog, a five-stage decision funnel is introduced to filter it by actor-specific structural boundaries and operational readiness. The illustrative application to vehicle electronics shows that no single action is universally applicable, and the set of suitable actions varies with the actor, temporal horizon, degree of control, and disruption profile. By making actor-specific feasibility and inter-action dependencies explicit, the framework enables companies and countries to assemble coherent mitigation portfolios rather than deploying isolated actions whose prerequisites, amplifications, or contradictions remain unexamined.

1. Introduction & motivation

Criticality assessments aim to inform decision-making on the likelihood and vulnerability of supply disruptions. The ultimate goal is to mitigate the consequences of disruptions for economies, sectors, and companies (Kolotzek et al., 2018). In practice, a gap persists between diagnosis, as reflected in criticality indicators, and prescription in the form of actionable mitigation strategies (Otterbach and Fröhling, 2025). Most assessments end with generalized policy recommendations or short action catalogs that lack prioritization, actor specificity, or temporal logic. China's 2023 export licensing requirement on gallium and germanium targeted materials, already identified as critical by multiple assessments, yet the analysis revealed that most downstream actors had no pre-positioned mitigation capabilities in place (Nassar et al., 2024). Single, initial actions, such as limited stockpiling, were in place, but a structured pathway from assessment to actionable preparedness was missing. The European Court of Auditors (2026) finds that the EU's critical raw materials policy rests on incomplete foundations, lacks clearly justified targets, and has not produced tangible results, while bottlenecks continue to hamper domestic production and the circular

economy (European Court of Auditors, 2026). While it is recognized that the existence of a strategy does not imply the capability to execute it (Bruckler et al., 2024), this distinction is rarely operationalized at the level of individual mitigation actions. Rather, mitigation actions are treated as selectable instruments, and it is implicitly assumed that actors possess the capabilities required to implement them.

Frameworks such as Wietschel et al. (2025) integrate criticality and resilience at the assessment level, but a structured method for translating assessment results into concrete mitigation actions that account for actor-specific capabilities and contextual constraints remains missing. A structured mapping of action dependencies, implementation prerequisites, and feasibility rules extends current research by specifying when and how actions can be operationalized.

This research addresses the gap through two research questions:

- ❖ RQ1: How can mitigation actions be classified with respect to their dependencies, and their potential to reduce the likelihood, mitigate the effect, and accelerate recovery from supply disruptions?
- ❖ RQ2: How can mitigation actions be operationalized given actor-specific implementation capabilities and constraints?

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The present framework deliberately operates at the action level rather than the assessment level. The quality of the resulting mitigation portfolio depends heavily on the quality of the assessment inputs. To illustrate how the catalog can be coupled with assessment results, a mapping between actions and combinations of three disruption pathway types (physical, cost, and structural) is presented.

2. Methodology

2.1. State of the research

Criticality assessments evaluate the risk of material supply disruption along two dimensions: the likelihood of disruption and the vulnerability to its impact. Indicator-based assessments have been repeatedly critiqued for weak causal grounding, inconsistent aggregation, and the absence of severity-duration representation (Andrieu et al., 2026; Frenzel et al., 2017; Glöser et al., 2015). Supply chain resilience research complements this by addressing how systems absorb, adapt to, and recover from disruptions, with capacities classified as absorptive, restorative, adaptive, and transformative (Bruckler et al., 2024; Elmqvist et al., 2019; Hosseini et al., 2019). Resilience frameworks have been applied to material supply chains, including the 2010 rare-earth crisis (Sprecher et al., 2015, 2017). Wietschel et al. (2025) proposed an integrated three-dimensional structure, focusing on reducing likelihood, mitigating effect, and accelerating recovery from supply disruptions, as a conceptual bridge between the two streams, although its scope remains the assessment of disruptions rather than the selection of responses. Both fields treat mitigation actions as generic instruments that can be deployed once a risk is identified, offering limited insight into how actors should respond or which actions are feasible in practice.

The mitigation literature reflects this limitation. A large share of studies adopts an outcome-oriented approach, evaluating the effectiveness of individual actions, such as financial hedging (Al Wahaibi, 2025) or comparing multiple actions within sectoral case studies, for example, photovoltaic (Gervais et al., 2025), semiconductor (Xiong et al., 2025), or chemical supply chains (Behdani et al., 2019). Others investigate mitigation actions for multiple strategic technologies and sectors combined (Bobba et al., 2020). Several studies structure mitigation actions by mapping them to resilience capabilities (Bruckler et al., 2024; Griffin et al., 2019), disruption dimensions (Otterbach and Fröhling, 2025; Rajagopal et al., 2017), interrelationships (Hosseini et al., 2019; Sprecher et al., 2015), or sustainability implications (Doetsch and Huchzermeier, 2024). A smaller group compiles mitigation actions through general (Ren et al., 2024; Sudan et al., 2023) or domain-specific

(Gould et al., 2010) literature reviews. Across these contributions, the feasibility of implementing mitigation actions receives limited consideration. Questions such as when and for whom individual actions are executable have not been operationalized. This work addresses that gap by translating the three-dimensional framework of Wietschel et al. (2025) into a mitigation action selection logic accounting for actor-specific, structural boundaries, operational readiness, and action dependencies. The framework is thereby extended from the assessment level, where disruptions are measured, to the action level, where responses are selected.

2.2. Conceptual framing of the bridging logic

To bridge the gap between the criticality assessment level and the action level, this study translates fragmented mitigation literature into an operational framework for supply chain resilience portfolios. Fig. 1 provides an overview of how the criticality and resilience assessment view relates to the sphere of supply disruption risk mitigation. On the left side, the assessment of criticality and resilience is decomposed into supply risk, vulnerability, and resilience. This follows the three-dimensional framework proposed by Wietschel et al. (2025), which links these assessments to the (i) likelihood of disruption, (ii) effect of disruption, and (iii) recovery from disruption. The central dashed line splits the assessment level from the action level. On the action level, mitigation is organized along the same dimensions. In a similar way to assessment indicators, mitigation actions can be characterized by whether they reduce the probability of disruption, limit its effect, or improve recovery. This parallelism highlights that mitigation actions are causally related to specific dimensions of disruption.

The inclusion of the capability-building arrow emphasizes that mitigation actions cannot always be implemented immediately, as some require prior capability development. These capabilities enable the implementation of actions that, in turn, intervene in the respective dimensions of disruption.

2.3. Compilation and harmonization of mitigation actions

Literature on mitigation actions to enhance supply chain resilience is not scarce but remains fragmented. A comprehensive literature search was conducted to collect mitigation actions from current research. The systematic review applied two Boolean strings to five databases ScienceDirect, Web of Science, SpringerLink, Wiley Online Library, and IEEE and restricted the search to English-language journal articles published from 2000 to 2025. The second Boolean string is very similar to the first

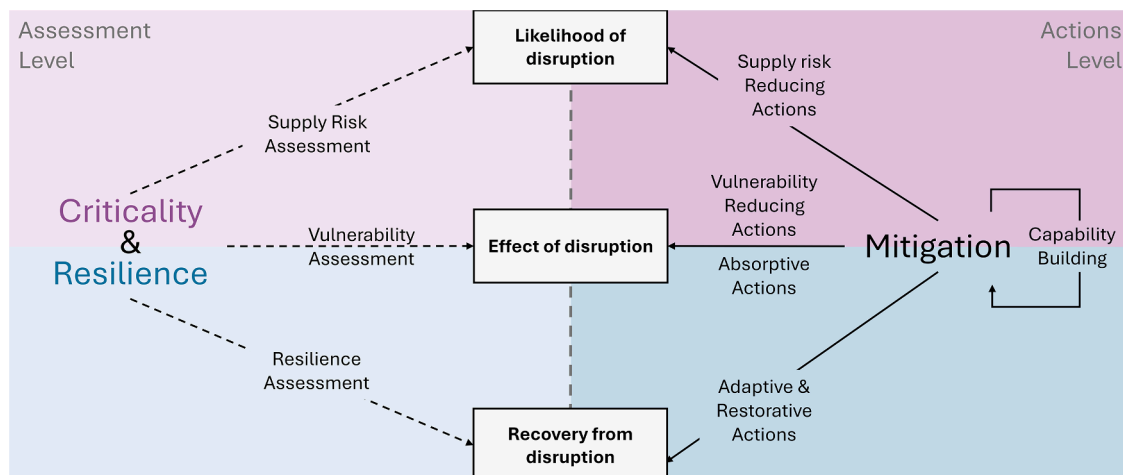


Fig. 1. Overview of the conceptual bridging of criticality assessment and mitigation actions. Dashed arrows convey information derived from the assessments, while solid arrows represent intended interventions through mitigation actions.

one with an added focus on critical raw materials to improve coverage in that research field. The searches returned 317 records, from which 182 remained after manual duplicate removal by author-year-title matching. The articles were screened on title, abstract, and keywords against exclusion criteria “off-topic”, “no mitigation actions”, “no criticality or resilience relation”, or “full text not retrievable”. Uncertain cases were resolved by full-text screening. This process yielded 53 studies. Backward and forward citation searching and known key papers added 34 articles. This led to a total of 87 identified studies that contain mitigation actions in the context of supply chain resilience and criticality. The literature search procedure is described in more detail in the Supplementary Document 1 (Section S1).

Raw literature entries for mitigation actions were extracted verbatim and coded by reference, the actor mentioned, and context. This ensured that each observation retained its original conceptual framing. Actions were grouped using an iterative semantic consolidation process. Actions exhibiting semantic overlap (e.g., “stockpiling” vs. “buffer inventories”) that describe conceptually identical practices were grouped into a single harmonized action. Ambiguities were retained when the conceptual boundaries in the source literature remained unclear. After harmonization and deduplication, the 796 actions mentioned in the literature were grouped into 139 distinct actions, each assigned a unique identifier (A01 to K02). The whole list of actions is presented in Supplementary Document 2, in the sheet “Harmonized_actions”.

2.4. Action classification

To use the consolidated mitigation action catalog as a decision framework for action operationalization, each harmonized action was classified along seven axes, described below:

Mechanism: The mechanism classification assigns each action to one of 11 core action mechanisms shown in Table 1. The mechanisms were defined through an inductive process of grouping the harmonized action catalog by the instrument through which each action operates, for example the type of lever an actor deploys, such as a contract, a regulation, a technology change, an information system, or a physical or structural change to the supply chain. This principle differs from common groupings that sort actions by resilience capacity, distinguishing between absorptive, adaptive, restorative, or proactive roles in the recovery from a disruption, or groupings by the risk type the actions respond to. The mechanism logic adds an instrument-oriented axis across the action catalog. Existing classification schemes of mitigation actions in relation to this study’s grouping, as well as mechanism boundary definitions, are provided in Supplementary Document 1 (Section S2).

Actor applicability: Actions are mapped to the actor class that can implement them, restricted to “Company” or “Country”. This distinction is a strict constraint. The two actor classes are not aggregable or interchangeable, as they differ structurally and operate under fundamentally different institutional logics, decision-making horizons, available instruments, and accountability structures. Practices that both actors can pursue are represented as actor-specific action variants rather than dual-coded entries, because instruments, scale, and degree of control differ between a company and a country (e.g., stockpile build-up (H07, company) vs. strategic/national stockpile build-up (H04, country)). Joint or co-funded arrangements are represented as combinations of such variants, connected through cross-actor relationships in the dependency matrix. For example, substitution R&D (C01, company), R&D for material efficiency improvement (C02, company), and process innovation R&D (C03, company) are amplified by promoting R&D (C05, country) and innovation partnerships (C13, country).

Disruption dimension linkage: For the action level, three causal target categories are identified, each corresponding to one assessment dimension: (i) *likelihood-reduction* actions (e.g., supply diversification, trade agreements), (ii) *effect-mitigation* actions (e.g., stockpiles, hedging, cost pass-through), and (iii) *recovery-acceleration* actions (e.g.,

Table 1

Identified risk mitigation action mechanisms with Mechanism IDs (A-K) assigned in descending order of action count. The whole list of actions is detailed in Supplementary Document 2, in the sheet “Harmonized_actions”.

ID	Mechanism	Description	Example actions
A	Contractual & financial stabilization	Legal agreements and financial instruments that hedge price or volume risk through private commercial channels. Includes contract structures, hedging instruments, and financial prerequisites.	A03 Financial hedging A04 Flexible supply contracts A07 Spot market procurement
B	Governance & geopolitical strategy	Sovereign policy instruments, diplomatic channels, regulatory mandates, and institutional coordination.	B02 Import taxation & tariffs B10 Regulatory framework for Extended Producer Responsibility (EPR) B18 Enforce compliance, standardization & certification
C	Technological adaptation	Research, development, and technology adoption that change the materials used, processes employed, or products manufactured.	C04 Technology substitution C07 Material substitution C08 Process adaptation
D	Information & monitoring	Generation, processing, and exchange of information to improve decision-making regarding supply disruptions.	D01 Supply chain information sharing & coordination D02 Strategic material classification & criticality assessment D05 Implement digital analytics/AI
E	Circular supply creation	Secondary material flows that supplement or replace primary supplies. Includes infrastructure development, loop-closing measures, and secondary-market structures.	E01 Recycling capacity build-up E05 Material efficiency improvement E11 Remanufacturing
F	Structural reconfiguration	Architectural changes to the supply chain’s topology, ownership structure, or operational logic.	F03 Re-/Friend-/Nearshoring supply chain F04 Supplier protection F12 Supplier selection & allocation
G	Organizational capability building	Meta-capabilities: the internal human, institutional, and procedural foundations on which other mechanism-specific actions depend.	G01 Education & training programs G04 Institutional coordination platform G06 Flexible production & demand management
H	Absorptive capacity (buffering)	Physical reserves and unused capacity that decouple disruption onset from production impact. Reserves are built via accumulation measures and drawn down via activation measures.	H02 Use stockpile H05 Facility fortification & physical protection H06 Production capacity buffer
I	Primary supply expansion	Expansion of virgin material volume in the upstream sector through exploration, extraction, yield maximization, and production policy support.	I02 Conventional deposit extraction I05 Non-conventional deposit exploration & development I08 Extraction yield maximization
J	Redundancy creation	Alternative supply routes that ensure that failure of a single node does not halt operations.	J04 Multi region sourcing J05 Supplier diversification J08 Contract backup suppliers
K	Demand-side reduction	Reduction in demand alone, without changes in supply, substitution, or efficiency gains.	K01 Demand reduction / Sufficiency strategies K02 Establish assortment planning

substitution, recycling, R&D). Mitigation actions are interpreted as interventions that operate on one or more of these dimensions.

Disruption pathway types: The disruption pathway type further differentiates between *physical disruption*, where the action directly increases the probability of material being physically available, *cost increase*, where the action mitigates financial exposure but does not increase physical availability, and *indirect/structural*, where the action is primarily governance, or framework setting, with physical or cost effects only indirectly mediated and long-term. Combinations of the three types are possible.

Temporal and control properties: This classification layer captures when an action takes effect after initiation and the degree of control the actor has over executing it. *Time to impact* measures the expected duration between initiating the action and observing mitigation effects, ranging from immediate (<1 month), short-term (1–12 months), medium-term (1–5 years), to long-term (>5 years). *Degree of control* captures the actors' implementation autonomy, ranging from high internal control (actions can be implemented largely independently) to low internal control (actions require approval, cooperation, preparation, and implementation by other actors or external entities).

Capability type: Actions are decomposed into three capability types. *Capability-building* actions are preparatory actions taken before a disruption occurs (e.g., building stockpiles for rare earths). *Capability-activation* actions are deployments of previously built capabilities during or after a disruption (e.g., using stockpiled rare earths). *Direct* actions do not require prior building phases (e.g., cost pass-through due to higher rare earth sourcing prices). This separation prevents the common conflation of preparedness with response into undifferentiated “resilience practices” that obscure feasibility and causality (Pires Ribeiro and Barbosa-Povoa, 2018; Ponomarov and Holcomb, 2009). Within the dataset, capability types are assigned rule-based as “building” if the action is a prerequisite for another action, “activation” if the action has a prerequisite action and is not a prerequisite for other actions, or “direct” if there are no prerequisite relations at all. In three cases where the action is capability-building without an activation act (for example, facility fortification & physical protection, expanding health and safety

infrastructure), manual adjustments were made.

Dependencies: Actions are classified by how they relate to one another to determine system behavior in combination and enable consistent portfolio construction. Three relationship types are encoded: *prerequisite* (pursuit of action B without prior action A is not possible), *amplification* (pursuit of action A increases the effectiveness of action B), and *contradiction* (pursuit of action A weakens the effectiveness of action B). Contradictions are context-dependent rather than absolute. For example, stockpiling and substitution may conflict when stockpiling a material that is no longer needed after the substitution. Stockpiling might also reduce the urgency for substitution R&D, as price shocks are temporarily buffered, but it can be complementary when stockpiling provides a time buffer during that urgency.

2.5. Decision funnel

Mitigation is limited not by lack of action options but by actor-dependent feasibility of operationalization. The decision funnel provides structured decision support, making intuitive, case study-based selection explicit and analytically traceable. It transforms the general action catalog into an actor-specific deployable action space through five filter stages organized into three sequential blocks (Fig. 2).

The first block establishes structural boundaries through non-compensatory hard constraints (Filter 1–2). The second block assesses operational readiness through adjustable threshold trade-offs (Filter 3–4). The third block performs a portfolio-level consistency check (Filter 5).

Filter stages 1 and 2 apply attribute-based elimination (Bettman et al., 1998). Actions failing a criterion are removed and cannot be recovered by later scores. Compensatory multi-criteria methods (e.g., AHP, TOPSIS) were rejected because actor applicability and pathway relevance are hard boundaries rather than weighted trade-offs. Both criteria are fixed properties of the decision context, as institutional identity does not shift across planning cycles, and the disruption pathway is determined by the material-specific risk profile rather than actor preference. Filters 3 and 4 assess the deployability within the

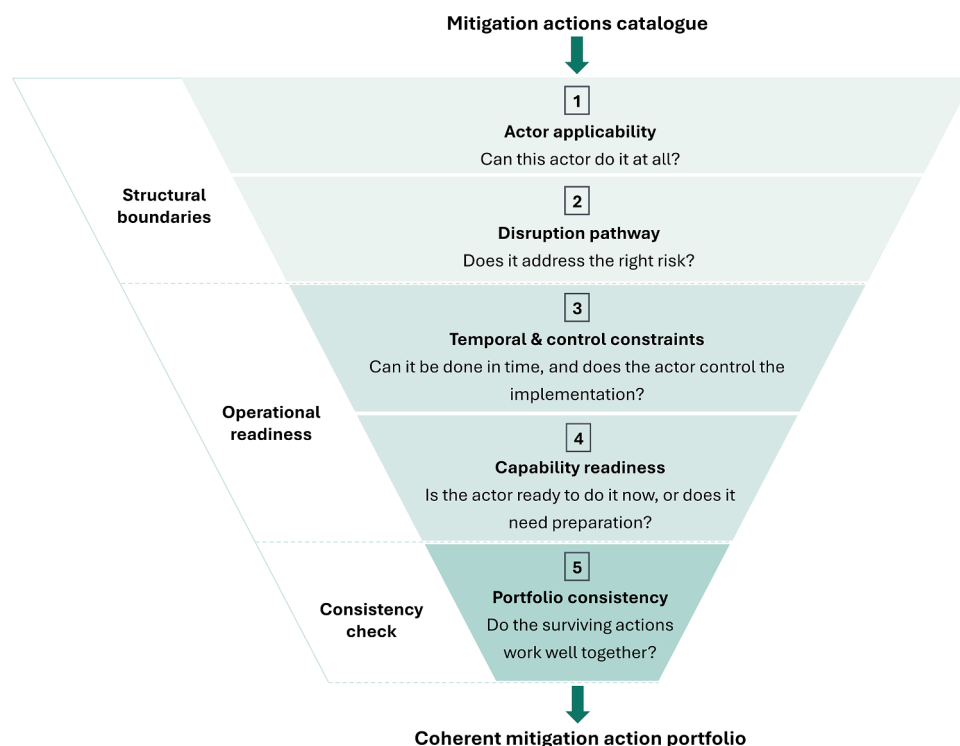


Fig. 2. Decision funnel to an actor-specific coherent mitigation portfolio.

surviving action space and operate as adjustable thresholds rather than fixed boundaries, following a decreasing-abstraction logic analogous to Stage-Gate (Cooper, 2008). Different actors may set different thresholds, for example, depending on whether they face acute disruption or engage in strategic planning. Filter 5 brings all actions into context with each other. All filter stages are described in detail in the following:

Filter 1: Actor applicability. The first filter restricts the action catalog to only those actions the actor is institutionally capable of executing.

Filter 2: Disruption pathway types. The second filter retains actions matched to the relevant disruption pathway type (see Section 2.4). Combining the funnel with a quantitative risk assessment (e.g., Nassar et al. (2025)) requires additional scenario-sensitive, threshold-based matching at this step and is out of scope of this work.

Filter 3: Temporal and control constraints. The third filter applies time-to-impact and the degree of control thresholds (see Section 2.4).

Filter 4: Capability readiness. The fourth filter applies the building-activation-direct logic (see Section 2.4) of actions viable now (direct), actions building capacities (building), and actions whose prerequisites are already implemented (activation).

Filter 5: Portfolio consistency. The fifth filter is a coherence check on the surviving mitigation set rather than a per-action criterion. It identifies the prerequisite, amplification, or contradiction dependencies defined in Section 2.4 to enable the actor to compose a mitigation portfolio without tensions.

Criticality assessment outputs indirectly and non-systematically

enter the funnel at defined points. Supply concentration, import dependence, and geopolitical exposure indicate the dominant disruption pathway and thereby feed Filter 2. Project lead-time constraints and the urgency of the assessed risk inform the time-to-impact and control thresholds in Filter 3. Substitutability and recycling potential condition the relevance of technological adaptation and circular supply actions within the surviving action space, and the relative severity of the assessed risk dimensions can guide the actor in ranking the actions after composing the portfolio in Filter 5. The interactive Decision Funnel tool (“CritMitNavigator”) is available in the OSF repository (see Data availability).

3. Results

3.1. Consolidated action catalog

The literature review confirms that mitigation actions are largely treated as discrete, available options that can be implemented if selected. Less attention has been given to the distinction between the availability of an action and the capability required to execute it. In particular, the question of when and for whom an action is feasible has received limited systematic consideration.

Mitigation strategy selection depends on context and goal. The framework, therefore, does not prescribe actions but structures the decision space, enabling actors to systematically narrow the full action catalog to a context-appropriate action portfolio.

The harmonized action catalog comprises 139 actions across 11 action mechanisms. The distribution of the action catalog across actor

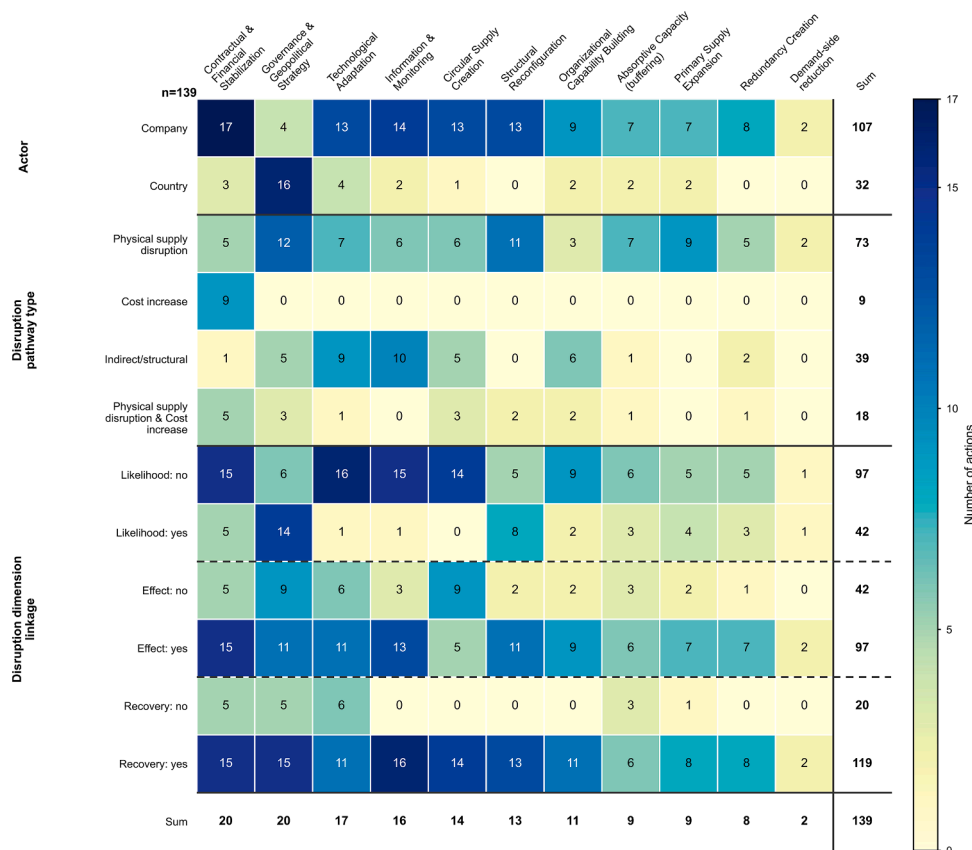


Fig. 3. Distribution of action catalog ($n = 139$) across actor applicability, disruption pathway type, and disruption dimension linkage (rows), broken down by the 11 mechanisms (columns) into numbers of actions (cell value). Actor and pathway assignments are unique per action, with pathway combinations forming a separate category. A single action can address several disruption dimensions, so the “yes” counts of the three dimensions do not sum to 139. The whole list of actions with all classification assignments is provided in Supplementary Document 2, sheet “Harmonized_actions”. A condensed version with the columns relevant for filters 1 to 3 is given in Supplementary Document 1 (Table S1).

applicability, disruption pathway types, and disruption dimension linkages is summarized in Fig. 3. The actor distribution shows asymmetry between companies' and countries' action spaces. The latter mostly consists of actions within the "Governance & Geopolitical Strategy" mechanism, whereas companies have a larger number of catalogued actions across different mechanisms. This is because company-level operational responses can be more diverse, while countries primarily operate through regulatory, diplomatic, and financial instruments. The divergence can also stem from companies receiving more attention in the mitigation literature so far. Recovery is the most widely covered dimension (119 of 139), followed by effect reduction (97) and likelihood reduction (42), the latter being the least-covered dimension. These counts describe the composition of the harmonized catalog, not the magnitude of mitigation potential. Harmonized actions differ in breadth; promoting R&D (C05) spans an entire policy field, whereas process innovation R&D (C03) targets one specific R&D type, while each enters the count as one single entry. The mechanisms most strongly linked to likelihood reduction are Governance & Geopolitical Strategy and Structural Reconfiguration. Both are forward-looking mechanisms through which countries and companies can actively reduce their likelihood of disruption. Effect-linked actions absorb impact, limit propagation, or buffer the shortfall to reduce the disruption impact in real time. Recovery-linked actions enable a return to normal operations after the disruption. There is a strong overlap between effect reduction and recovery actions (90 of 139 actions), as many actions that absorb impact also enable recovery. For example, through flexible supply contracts (A04) companies can adjust supply volume and timing to limit the damage during a disruption and accelerate the return once the disruption eases.

3.2. Dependency structure

Dependency modeling maps a network layer onto the mitigation portfolio, revealing contradictory and amplifying effects among actions. This demonstrates that mitigation actions exhibit system behavior, and resilience is built through coherent action systems rather than through single actions. The dependency matrix captures directed source-to-target relationships between actions, encoded as the three relationship types defined in Section 2.4 (prerequisite, amplification, contradiction). It records only relationships substantiated in the coded literature corpus or the harmonization analysis, it is deliberately not an exhaustive assessment of every possible action pair.

The prerequisite relationship dominates, confirming that most actions in the action space are not independent; trying to pursue individual actions in isolation ignores prerequisite chains and opportunities for synergy. All contradiction relations are reciprocal, whereas amplification relations are frequently, but not always, mutual, so their direction carries information. Roughly a quarter of all relationships span the company-country boundary, linking the two actor-specific action spaces. Connectivity concentrates on the Governance & Geopolitical Strategy and Information & Monitoring mechanisms. Relative to mechanism size, Information & Monitoring and Circular Supply Creation actions are the most densely connected. For example, end-of-life recycling (E08) requires reverse logistics and collection structures (E07), which in turn require CAPEX financing capability (A09), while nearshoring the supply chain (F03, company) requires domestic extraction and production policy support (I06, country). One example of a contradictory relationship is investing in substitution R&D (C01) to develop alternatives to a critical material, which contradicts simultaneous stockpile build-up (H07) for that same material, because successful substitution would render the stockpile obsolete, wasting the sunk investment in reserves. Also, deep stockpiles reduce perceived urgency for substitution investment. All dependencies and the authors' rationale behind them are listed in Supplementary Document 2, sheet "Dependency_matrix". How these relations shape actor-specific portfolio selection is illustrated for the vehicle electronics case in Section 4

(Figs. 4 and 5).

4. Illustrative application: vehicle electronics

The assumed actor in this illustrative case is stylized as an automotive company. Parameter choices in Filters 1 to 4 represent the typical expected behavior of this type of company, and not firm-specific conditions. This illustrative case aims to demonstrate how the funnel structures portfolio selection under stated assumptions, not that the resulting portfolio matches observed company behavior or realized disruption outcomes.

In recent years, the fragility of the automotive sector's supply chain, particularly in electronic components and their raw materials production stages, has been discussed (e.g., Yang et al. (2025) and Xiong et al. (2025)). The literature documents high-concentration risks in the gallium and rare-earth supply (e.g., China-dominated refining), geopolitical exposure, and just-in-time automotive supply chains (Mancheri et al., 2019; Sprecher et al., 2015). Semiconductor architectures are technologically path-dependent with limited short-term substitution potential. Furthermore, any change in the material used, or even in its purity grade and unique properties, depending on the material's provenance and supplier, might result in performance loss and increased costs. Expensive, time-intensive changes to the design of key components and production processes might also be required. Perossa et al. (2026) report a criticality assessment for the raw materials used in the electronic components of a typical large European automotive firm. The results show a high level of supply risk for several materials, particularly tantalum, gallium, germanium, tungsten, and indium. The main causes lie in supply concentration and low cooperation between Europe and the countries where suppliers are based (i.e., high risk of trade restrictions). Besides supply risk, other dimensions were found to be concerning, such as competition among sectors for access to raw materials (indium, gallium, and germanium) and substitutability (all the assessed materials, except copper, were found non-substitutable).

Based on these considerations, the following characterization can be made for supply risks and resilience in this context: (i) **Likelihood** is assessed as high, driven by market concentration and trade restriction risk; (ii) **Effect** is equally high, as production stoppages cascade through OEM networks; and (iii) **Recovery** is medium, reflecting very limited short-term substitution potential, while medium-term recycling and diversification remain feasible.

The actions excluded at the application of each filter are listed in Supplementary Document 3, in the sheet "Filter_cascade_python_generated".

4.1. Application of Filter 1: actor applicability

Filter one concerns the actions that fall within the normal capabilities of the considered type of actor. As mentioned above, in this illustrative case it has been assumed the actor is a company. The actions have been thus filtered accordingly, excluding those that cannot be carried out by an enterprise.

4.2. Application of Filter 2: disruption pathway types

The considered sector is characterized by a high structural risk, due to, among others, the high concentration on only a few upstream supplier companies in key stages of the value chain (Perossa et al., 2026). The physical availability risk is also present and linked to the sector's supply chain structures and the current geopolitical context (Bobba et al., 2020). Price increases are also a concern in this sector, but given the recent risks of physical supply disruptions (e.g., the Nexperia case (Bounds and Inagaki, 2025)) and the fear of future geopolitical events that could affect supply availability, it is assumed the company wants to focus on the physical risk. This is the substantive risk that, if realized, puts the company's survival at stake.

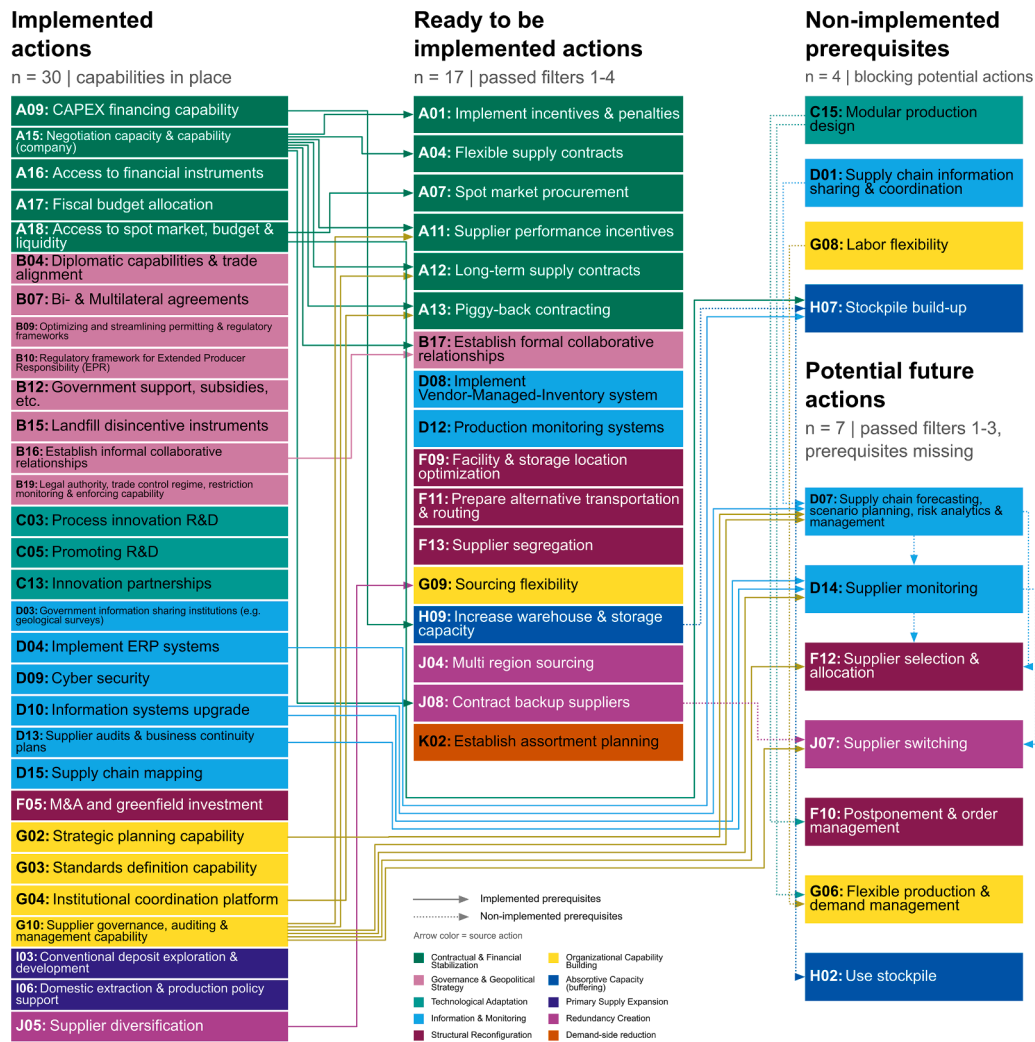


Fig. 4. Action selection for the vehicle electronics use case (automotive company, physical supply disruption pathway, immediate and short-term actions under high internal control) taking into account capability readiness. Left column: actions assumed already implemented (n = 30); middle column: actions that passed filters 1 to 4 and are ready to be implemented (n = 17); top right column: the non-implemented prerequisites blocking the potential future actions (n = 4); bottom right column: potential future actions that passed filters 1 to 3 but lack at least one prerequisite (n = 7). Every arrow denotes the same relation, a building (prerequisite) dependency, pointing from prerequisite to dependent action. The status of a prerequisite follows from the column of its source. Arrows from implemented actions (left) mark prerequisites already satisfied and have a solid line style. Arrows from non-implemented prerequisites or between potential actions mark prerequisites still missing and have a dotted line style. Arrow color repeats the mechanism color of the source action, is used for clarity, and has no other significance.

4.3. Application of Filter 3: temporal and control constraints

Regarding control constraints, it is reasonable to assume the company wants to focus on actions it can control effectively (Miller, 1992). For this reason, only actions with high internal control are considered. Furthermore, in this illustrative case, it is assumed that the company wants to focus only on actions it can pursue within one year (i.e., immediate and short-term actions). This horizon reflects the immediate geopolitical uncertainty and rising near-term demand from sectors such as data centers (Schneider, 2026; Xiong and Sun, 2025).

4.4. Application of Filter 4: capability readiness

To apply filter 4, it has been evaluated, based on the assumptions below, whether, on average, the standard automotive company in the later stages of the supply chain pursues the prerequisite actions identified after applying the previous filters (see Supplementary Document 3, the sheet “Implemented actions”). The types of companies considered are usually large. Therefore, they possess advanced IT systems, have entire divisions devoted to R&D, and have access to substantial financial

resources. They are used to managing relations with several suppliers. However, in long and complex supply chains, visibility is very limited. Car makers and component assemblers are typically based in wealthier countries with active R&D grant systems and an established diplomatic capacity for strategic supplies. However, a significant limitation for these types of firms is that they often miss out on opportunities to implement higher-circularity strategies in the circular economy (Prochatzki et al., 2023). Additionally, decades of lean management in the automotive sector (Holweg, 2007) mean that large stockpiles are rarely held.

4.5. Application of Filter 5: portfolio consistency

Fig. 4 shows the selected mitigation actions and their dependencies, including links to actions implemented earlier (cf. Filter 4). A total of 17 actions ready to be implemented have been identified, with 7 further actions being implementable once their missing prerequisites are established. They are all listed in the Supplementary Document 3, in the “Filter_cascade_python_generated” sheet. Actions executable by an actor are restricted to that actor's class, but cross-actor prerequisites are added

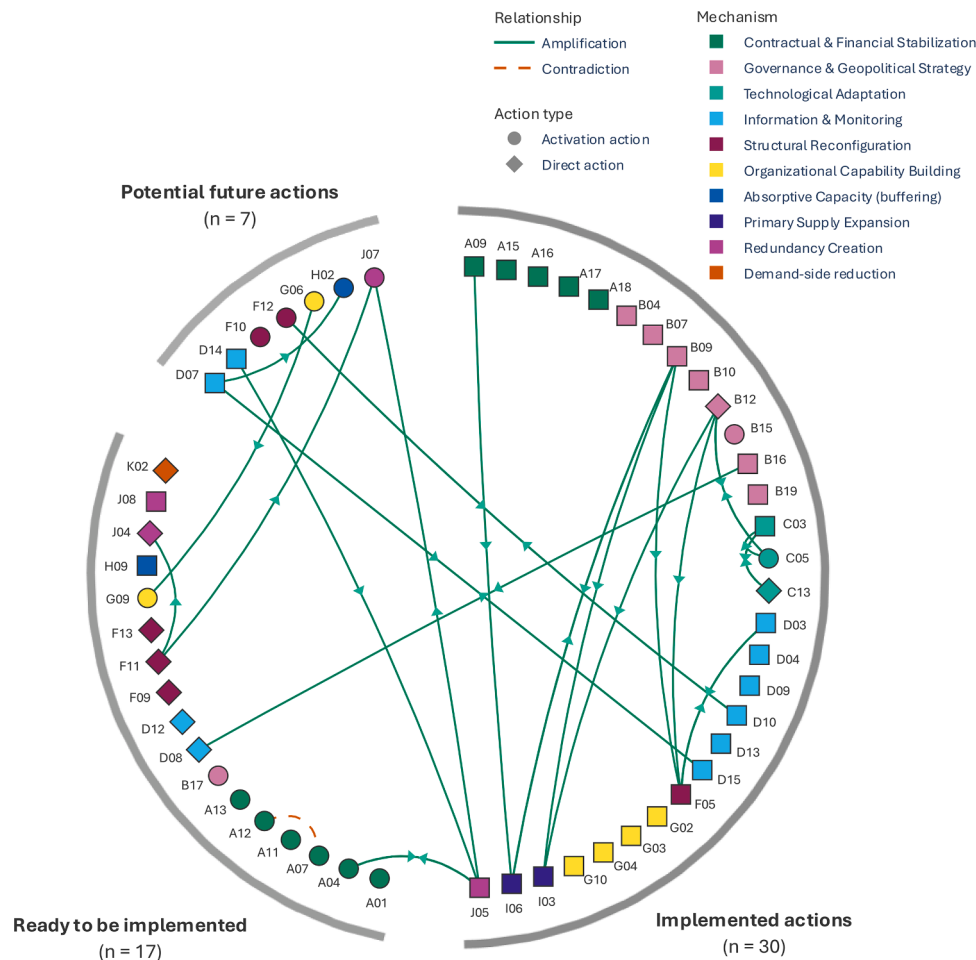


Fig. 5. Amplification (green, solid) and contradiction (orange, dashed) relationships among the 54 actions of the vehicle electronics use case grouped into implemented ($n = 30$), ready to be implemented ($n = 17$), and potential future actions ($n = 7$). Amplification arrows point from the reinforcing to the reinforced action. Contradictions are mutual. Node color denotes the action mechanism, node shape the capability type (square: building (prerequisites), circle: activation, diamond: direct). For conciseness the same action IDs as in Figure 4 without action names are used. Amplifications dominate (27 relations), while the portfolio contains a single contradiction, spot market procurement (A07) versus long-term supply contracts (A12), a procurement-strategy trade-off rather than an infeasibility.

to the dependency graph.

As specified in this illustrative case, as a result of the proposed framework, an automotive company would now be able to visualize the pool of implementable actions they have at their disposal to mitigate the supply risk of raw materials used in electronic components. As shown in Fig. 5, the company might also identify what actions from this pool amplify each other and what actions are instead contradicting each other. Below, some examples of the evaluations that are now enabled are reported.

The CAPEX financing capability (A09) that large automotive companies typically possess can be utilized to increase the warehouse and storage capacity (H09). This enables stockpile build-up (H07), which unblocks actions like the consumption of such stockpiles, shielding the company significantly from shortages. A few financial and contractual stabilization actions can also be easily implemented. Among them, flexible supply contracts (A04) amplify the already implemented supplier diversification (J05). This would enable a more flexible management of the supplies in times of shortages. Another action ready to be pursued is “implement vendor-managed-inventory system” (D08), which is amplified by the already implemented “establish informal collaborative relationships” (B16), leading to an overall more resilient supply chain.

Among the non-implemented pre-requisites, supply chain information sharing and coordination (D01) emerges as of great relevance. It

would enable, together with other already implemented actions, the pursuit of supply chain forecasting, scenario planning, risk analytics & management (D07), which would then concur in enabling supplier monitoring (D14), supplier selection and allocation (F12), and supplier switching (J07) (which also requires contracting back-up suppliers (J08)). Supply chain forecasting, scenario planning, risk analytics & management (D07) is amplified by the already implemented supply chain mapping (D15). Supplier monitoring (D14) further amplifies the already implemented supplier diversification action (J05), which in turn amplifies supplier switching (J07). Supplier monitoring (D14) is also a prerequisite for supplier switching (J07).

The implementation of these actions, together with the others that are visible in Fig. 4 as ready to be implemented, would considerably decrease the supply risk of the raw materials. Other considerations related to constraints and effectiveness of each action should be performed to select those to be implemented from the pool obtained thanks to the proposed framework, as elaborated in Section 5.

The portfolio illustrates that even within a single actor and pathway, action selection is shaped by prerequisite chains and dependency consistency, not by ranking individual actions in isolation.

5. Discussion & conclusion

The framework advances the literature through three structurally

novel contributions. First, it maps mitigation actions causally onto the three disruption dimensions of [Wietschel et al. \(2025\)](#) (likelihood, effect, recovery), making explicit that interventions targeting one dimension do not automatically address the others. Dual-purpose actions are explicitly coded (for example, the production capacity buffer (H06), which reduces vulnerability and improves recovery). Second, the building-activation-direct typology separates preparedness from response, preventing the common conflation that leads to false assumptions about feasibility. Third, encoding prerequisite, amplification, and contradiction relationships establishes that mitigation portfolios exhibit system behavior rather than additive independence. Neither the causal action mapping, nor the capability typology, nor the dependency structure is part of the assessment-level framework of [Wietschel et al. \(2025\)](#), which this work extends toward operational decision support.

The framework narrows the action catalog into a feasible mitigation portfolio for actors. Its purpose is to structure the decision space, not to make the decision itself. Therefore, it omits aspects that vary significantly across actors and settings, such as estimation of implementation costs and effort. For the same reason, the variation in the severity and duration of disruption is not explicitly represented. This study focuses on mitigating the criticality of raw materials. External risks, such as transport disruptions or geopolitical conflicts, are considered only to the extent they translate into material supply risk. Broader cross-material dynamics, for example, changes in energy costs, are also not included. Incorporating these aspects would move beyond identifying feasible actions, as they require actor-specific data and assumptions that cannot be meaningfully generalized within the framework.

Material-system characteristics further condition both action feasibility and dependency interpretation. By-product dependence limits the responsiveness of primary supply expansion, as production volumes follow the host metal rather than demand for the by-product, as highlighted by [Bustamante et al. \(2018\)](#). Processing bottlenecks shift the binding constraint from extraction to refining, changing which redundancy and reshoring actions are effective. Recycling constraints, such as dissipative applications or long product lifetimes, cap the near-term contribution of circular supply creation. Technology lock-in raises the cost and duration of substitution, strengthening the case for buffering actions and weakening stockpiling vs. substitution contradictions in practice. Within the funnel, these characteristics enter qualitatively as material-specific conditioning of the risk profile in Filter 2 and of dependency interpretation in Filter 5, rather than as an additional filter stage.

A related boundary concerns strategic rather than exogenous disruptions. Export bans, coercive trade policies, and resource nationalism alter the likelihood of supply disruptions directly ([Mancheri et al., 2019](#)). The framework can identify appropriate measure portfolios for such cases, but under adversarial conditions, actions may trigger counter-responses and adaptive reactions that the framework does not model. Relevant instruments operating primarily at the likelihood-reduction level include diplomatic stabilization, strategic partnerships, coordinated purchasing alliances, trade countermeasures, and symmetrical and asymmetrical anti-coercion measures such as the EU Critical Raw Materials Act and the EU Anti-Coercion Instrument. Some of these can also influence recovery trajectories, for example, through shared R&D programs and coordinated stockpiling. Integrating adversarial dynamics would require game-theoretic or agent-based extensions that move beyond the action-structuring scope of this work.

Prior work demonstrates that mitigation actions generate feedback loops. Strategic stockpiling by one country may drive up prices for all in the short term and stabilize prices during crises, also for countries that did not stockpile ([Sprecher et al., 2015](#)). More broadly, actions taken by one actor may alter the decision space for others. Capturing such dynamics requires modeling system outcomes of actions over time. System dynamics modeling ([Li and Zobel, 2020](#)), time-dependent clustering of strategy effectiveness ([Otterbach and Fröhling, 2025](#)), and evaluation of mitigation performance under ripple effects ([Dolgui et al., 2018](#)) have

advanced this direction, but no existing approach systematically connects feedback modeling to the actor-specific feasibility structures introduced here. This remains an open research frontier.

The framework is designed to be assessment-agnostic and to receive inputs from indicator-based assessments, quantitative risk analyses, such as [Nassar et al. \(2025\)](#), or company and country expert judgment. The fundamental critiques of current indicator-based criticality assessments articulated by [Andrieu et al. \(2026\)](#), [Frenzel et al. \(2017\)](#), and [Glöser et al. \(2015\)](#), particularly regarding the lack of validation, incorrect aggregation, and the absence of severity-duration, are acknowledged. The quality of the resulting mitigation portfolio depends on the quality of the assessment inputs. A structured pathway from assessment to action, as proposed here, therefore also sharpens the demands placed on assessment methodologies by making transparent which input dimensions the action selection logic requires.

This work does not answer questions of relative effectiveness, optimization, or implementation hierarchy, nor does it weigh actions by scope or magnitude. The role of the actor is to build on the structured set of feasible actions and determine which actions are most appropriate, how they should be combined, and in what sequence they should be implemented.

Future work can build on the framework in several directions: providing consistent, actor-specific input from criticality assessments; evaluating the effectiveness of actions within structured portfolios; optimizing the feasible set of actions; or simulating optimal action-implementation sequences. Several of these extensions can only be meaningfully realized in case-study applications that incorporate system dynamics and refine interaction dependencies under real operating conditions. Furthermore, in the future, it will be relevant to extend the proposed qualitative framework to a quantitative approach. To do so, it will be necessary to define parameters related to effectiveness and implementation simplicity that can be quantitatively assessed. In this way, it is possible to select, from the pool of feasible actions, those that are most convenient to implement. The quantitative data-driven representation of the filtering dimensions proposed here is a cue for future research. To achieve this, quantitative parameters to evaluate the actions will be designed. They might include the timeliness of the implementation against the expected timing of the considered risk of supply shortage or disruption, based on historical lead times, a rough estimation of the expected economic impacts and costs of implementation, based on forecasts and investment analysis; or a parameter estimating the expected effectiveness of the implemented actions in terms of impact on the physical availability of the raw materials, based on technical analysis. The feasibility of the actions in relation to the specific raw materials, for example availability of alternative suppliers or recyclability, will also need to be represented, since such case-dependent constraints can reduce or entirely offset the effectiveness of individual actions. Also, the interaction strengths among actions will be relevant to quantify.

This paper provides a novel, systematic, cross-action framework for bridging the assessment of raw material criticality and the selection of mitigation actions. By compiling 139 harmonized actions from 87 sources, introducing the building-activation-direct typology, and encoding 278 dependencies, the framework operationalizes the integrated criticality resilience structure of [Wietschel et al. \(2025\)](#) into a practical mitigation logic. The five-stage decision funnel framework enables actor-specific filtering and trade-off analysis. An illustrative application to vehicle electronics demonstrates how the framework enables actor-specific portfolio selection, while a full quantitative validation against observed mitigation behavior and applications across further sectors with distinct vulnerability profiles remain open.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Claude Opus

4.7 and Opus 5 to assist with data curation and programming data visualizations, as well as Grammarly and DeepL to improve readability, clarity, and grammar. After using those tools, the authors reviewed and edited the content as needed and take full responsibility for the published content.

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CRediT authorship contribution statement

Martin Hillenbrand: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Riccarda Hieke:** Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Daniele Perossa:** Writing – original draft, Methodology, Data curation, Conceptualization. **Paolo Rosa:** Writing – review & editing, Supervision. **Christoph Helbig:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christoph Helbig reports a consulting or advisory relationship with European Commission Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW). Daniele Perossa reports a consulting or advisory relationship with European Commission Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW). All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Supplementary Document 1: Supplementary information and graphs (PDF)

Supplementary Document 2: Tables with data of manuscript (XLSX)

Supplementary Document 3: Tables with case specifications (XLSX)

Data availability

Data are available as Supplementary Document 1, 2 and 3, as well as in the OSF Repository [Hillenbrand et al., 2026](https://doi.org/10.17605/OSF.IO/MH7BC) at [doi:10.17605/OSF.IO/MH7BC](https://doi.org/10.17605/OSF.IO/MH7BC).

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