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Prioritizing 6G supply-chain resilience policies with an evidence-calibrated DEMATEL–TOPSIS model

Jia-Ying Lyu

Department of Chemistry, National Kaohsiung Normal University, Kaohsiung 824, Taiwan

Corresponding to: Jia-Ying Lyu, Email: t4981@mail.nknu.edu.tw

Abstract: The transition from 5G-Advanced to IMT-2030 is occurring before the material and component architecture of 6G has stabilized. Governments nevertheless face immediate choices about diversification, domestic capacity, stockpiles, research alliances, recycling, supplier qualification, and technology controls. This study develops an evidence-calibrated decision model for prioritizing those policies without assuming that a fixed 6G bill of materials already exists. A structured evidence synthesis of 35 substantive records—four official data or policy sources and 31 peer-reviewed studies—was used to code twelve interdependent resilience criteria and seven policy alternatives. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) identified causal structure and systemic prominence; Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranked policy packages using the normalized prominence profile as a structural-salience baseline rather than as a claim about stakeholder preferences. Visibility and traceability, innovation compatibility, environmental compatibility, geopolitical-risk reduction, and administrative feasibility formed the net-causal group. Durability of dependence reduction received the highest prominence weight (0.103), followed by domestic and allied capacity (0.100) and scalability (0.092). Shared supplier qualification and certification platforms ranked first (closeness coefficient 0.816), ahead of joint research and standards alliances (0.637), recycling and substitution (0.576), and multi-sourcing (0.574). A6 remained first under equal weights, four policy scenarios, twelve leave-one-criterion-out tests, and 10,000 weight perturbations. These tests establish within-model stability under the reported weight changes; they do not constitute external stakeholder validation. The findings support a sequenced portfolio: build visibility and common qualification infrastructure first, use diversification and research alliances to expand feasible options, and reserve capital-intensive capacity, stockpiles, and controls for clearly diagnosed layer-specific bottlenecks.

Keywords: 6G, Supply-chain resilience, DEMATEL, TOPSIS, Critical materials, Technology policy

1. Introduction

The policy debate surrounding sixth-generation mobile communications is moving faster than the underlying industrial architecture. The International Telecommunication Union has established the IMT-2030 framework and identified broad usage scenarios and capability directions, but it has not specified a universal hardware design or a settled bill of materials [1]. Technical research anticipates combinations of higher-frequency communications, integrated sensing and communication, artificial-intelligence-native networking, reconfigurable radio environments, advanced edge computing, and new device architectures [2-8]. These expectations

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are consequential for industrial policy, yet they do not justify treating 6G as a single production chain with a fixed list of critical minerals. The material relevance of gallium, germanium, indium, tungsten, molybdenum, rare-earth inputs, compound-semiconductor substrates, and specialized process chemicals depends on frequency range, device architecture, manufacturing route, performance target, and the speed with which alternatives can be qualified. Recent empirical network analysis of semiconductor materials likewise locates vulnerability in the structure of intermediate supply links rather than in mining totals alone [9].

Governments cannot wait for complete technological certainty before making resilience decisions. Mineral production and processing are already concentrated in several strategically important segments. The 2026 United States Geological Survey (USGS) Mineral Commodity Summaries document continuing concentration and import dependence across a range of critical commodities relevant to electronics and advanced manufacturing [10]. These data do not establish that every 6G architecture will depend on the same country, mineral, or processing route. They do establish a defensible boundary condition: any future communications system drawing on high-purity materials, compound semiconductors, radio-frequency components, sensors, test equipment, and network hardware will inherit some pre-existing concentration and qualification risks. The analysis therefore treats mineral statistics as evidence about possible exposure layers, not as a fixed 6G bill of materials. A recent critical-mineral screening exercise is informative about extraction, processing and trade exposure, although its findings are not direct observations of 6G procurement [11].

The resulting policy problem is not a binary choice between open trade and self-sufficiency. Governments can support additional suppliers, finance domestic or allied processing, maintain strategic inventories, fund common testbeds, accelerate substitution and recycling, create shared qualification systems, or impose selective export controls and investment screening. These measures differ in cost, timing, technological specificity, environmental effects, geopolitical exposure, and durability. A stockpile can bridge a short interruption but cannot repair a persistent lack of qualified suppliers. A new refinery may reduce long-run dependence but take years to permit, finance, construct, commission, and qualify. Diversification can widen the visible supplier base while leaving the same upstream processor in place. Export controls can protect sensitive capability while also encouraging retaliation, fragmentation, and duplicate standards. Treating these instruments as interchangeable obscures the very trade-offs that policy design must resolve.

Across firm-level and network-level studies, resilience is associated with capabilities such as visibility, flexibility, coordination, supplier relationships, recovery and adaptation; these literatures do not estimate a single transferable effect for the emerging 6G ecosystem [12-20]. Production-network studies show that shocks propagate more strongly when inputs are specific, substitution is slow, and vulnerable nodes are central to downstream production [21-25]. Critical-material studies distinguish geological availability from usable supply and identify processing, policy and material-specific adjustment constraints; the relative importance of electronic-grade qualification in 6G remains to be established [26-29]. Studies of politically conditioned trade concern specific mechanisms: Fuchs and Klann [30] examine bilateral export responses to official Dalai Lama meetings, while Gowa and Mansfield analyze the relationship between political-military alliances and trade openness [31]. Farrell and Newman [32] explain how domestic institutional arrangements shape cross-border interdependence and, in their later account, identify the jurisdictional and institutional conditions under which central economic-network nodes can be used for observation or access denial [33]. Drezner's [34] assessment of creditor power finds important limits to the conversion of financial resources into political compellence. None of these sources measures the net effects of prospective 6G export controls. A recent synthesis of semiconductor supply-chain resilience provides industry-adjacent evidence concerning component shortages, tiered dependencies and mitigation choices, without estimating disruption effects for a commercial 6G supply chain [35]. Contemporary reviews classify resilience measures by disruption type and supply-network design, supporting the need to evaluate policy instruments as complementary rather than interchangeable choices [36].

The unresolved gap is therefore a decision-design problem rather than a lack of lists of risks. Existing resilience, production-network, critical-material, and interdependence literatures identify important mechanisms, but they do not jointly specify how a medium-sized economy should rank cross-layer 6G resilience instruments while the architecture is unsettled. DEMATEL and TOPSIS studies provide methodological precedents for directed-influence mapping and compensatory ranking, while using different uncertainty and elicitation designs [37-45]. They do not independently validate the present 6G policy scores or establish a new algorithm. This study does not claim a new DEMATEL or TOPSIS algorithm. Its methodological contribution is an application architecture that links a layered, pre-commercial technology representation to explicit evidence coding, separates structural salience from normative preference, and reports the policy sequence together with sensitivity boundaries. Recent semiconductor decision models similarly assess interacting challenges and mitigation responses; they do not establish the present ordinal matrices or stakeholder preferences [46].

That gap also explains why a multi-criteria design is appropriate. The alternatives trade off speed, cost, physical capacity, substitutability, environmental compatibility, geopolitical exposure, and institutional feasibility, and those criteria influence one another. DEMATEL is used first to map directed influence and distinguish systemic

prominence from net causal leverage; TOPSIS is then used to compare the balanced performance profiles of policy packages. Policy-preference scenarios are reported separately so that the baseline structural-salience weights are not misrepresented as a survey of social or governmental priorities. This sequencing connects the substantive policy problem to the decision method rather than treating MCDM as an add-on scoring exercise.

This study asks: Which policy alternatives should a medium-sized advanced economy prioritize to improve the resilience of the emerging 6G material and component ecosystem when the causal interdependence among resilience criteria is explicitly modelled? Two subsidiary questions follow. Which criteria act as net causes and therefore constitute enabling capabilities? How stable is the ranking when weights and policy preferences change?

The article makes three contributions. First, it develops a layered 6G supply-chain representation that separates mining and by-product recovery, refining and high-purity separation, electronic-grade materials and substrates, radio-frequency and terahertz components, network equipment, and deployment. The representation avoids the misleading claim that one mineral list can stand in for all architectures. Second, it specifies an auditable evidence-to-decision workflow for a pre-commercial policy problem: source roles, coding boundaries, a direct-influence matrix, a policy-performance matrix, and worked aggregation examples are explicitly linked, while the complete raw matrices and coding memoranda are designated as essential supplementary replication material. The novelty claimed here is this evidence architecture and policy application, not the classical DEMATEL or TOPSIS formulas themselves. Third, the analysis produces a policy sequence rather than a single universal prescription. The causal map identifies enabling capabilities that affect several instruments, whereas TOPSIS identifies which packages are closest to the stated baseline profile; scenario analysis then shows where that ranking is preference-sensitive.

The remainder of the article proceeds as follows. Section 2 develops the layered resilience framework and defines the criteria and policy alternatives. Section 3 explains the evidence corpus, coding protocol, DEMATEL and TOPSIS calculations, and robustness tests. Section 4 reports the causal structure and policy rankings. Section 5 interprets the results for 6G industrial policy and supply-chain governance. Section 6 discusses limitations, and Section 7 concludes.

2. A layered decision problem for the emerging 6G ecosystem

2.1 From technological vision to industrial exposure

The IMT-2030 framework establishes a direction of travel rather than a frozen engineering design [1]. Research on 6G discusses candidate capabilities, including integrated sensing, intelligent operation and tighter integration among communication, computation and physical environments; these remain technology scenarios rather than evidence of a fixed deployed hardware architecture [2-4]. Research on frequencies above 100 GHz identifies candidate bandwidth opportunities and engineering constraints, but does not show that such frequencies will be required in every 6G deployment [5]. Reconfigurable intelligent surfaces and smart radio environments may shift some functionality from active base-station hardware into programmable surfaces and distributed components [6-7]. AI-oriented 6G roadmaps describe potential changes to network control and resource allocation, not an empirically established 6G hardware procurement pattern [8]. These developments widen the plausible component set rather than narrowing it. Recent surveys and hardware-oriented studies describe integrated sensing and computation, reconfigurable surfaces, and AI-assisted sensing as architectural options, while also documenting their open engineering constraints [47-50].

For resilience analysis, the important implication is that dependence must be mapped by function and production stage. A material may be abundant at the mining stage yet concentrated at refining. A processed material may have multiple producers but only one or two suppliers capable of meeting electronic-grade purity or radio-frequency performance. A technically comparable device may not be a practical substitute until it passes redesign, reliability, interoperability, and operator qualification. Equipment software, test systems, advanced packaging, repair capability, and standards participation can become bottlenecks even when raw materials are available. The emerging 6G ecosystem is therefore better represented as a sequence of linked layers than as a commodity basket. Multi-tier network research has shown why visibility limited to first-tier suppliers can miss critical relationships; this is an analogy for the proposed 6G decision criteria, not 6G-specific causal identification [51].

Figure 1 presents the analytical design used to connect layered evidence to a decision output. Verified public evidence defines the system boundary and constrains the coding; structured coding translates explicit mechanisms into a direct-influence matrix and evaluates policy alternatives against a common rubric; DEMATEL distinguishes systemic prominence from net causal influence; TOPSIS ranks alternatives; and sensitivity tests examine dependence on weight profiles and criterion inclusion.

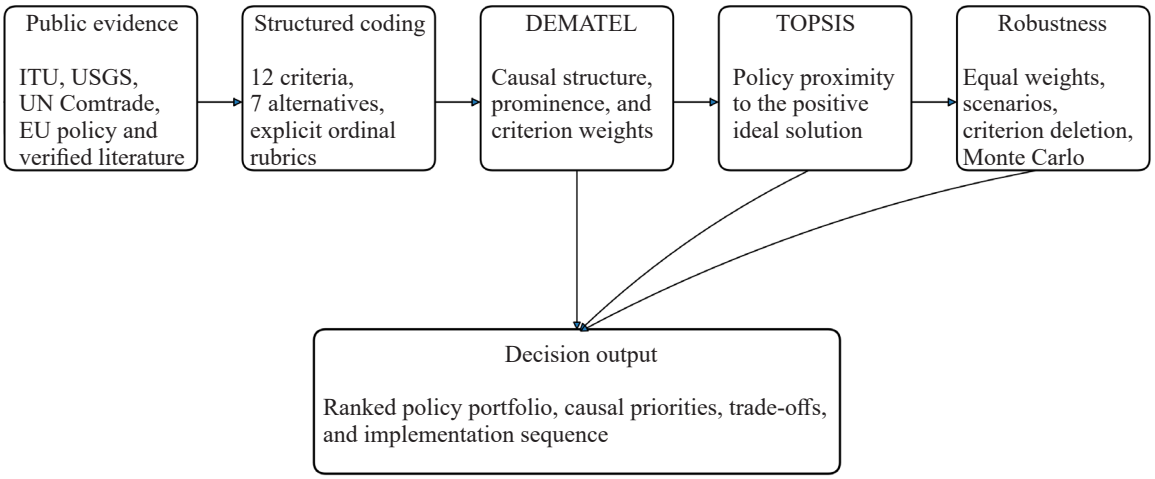


Figure 1. Research design for the evidence-calibrated DEMATEL–TOPSIS model

The chain itself is shown in Figure 2. Mining and by-product recovery feed refining and high-purity separation; these stages feed electronic-grade materials, substrates, and wafers; component production then supports network equipment and deployment. The arrows should not be read as a complete engineering bill of materials. They indicate where interruption, concentration, and qualification problems can arise. The lower part of the figure shows that policy alternatives are cross-layer interventions. Diversification affects mining, refining, and materials. Domestic or allied capacity can target refining, substrates, components, or test infrastructure. Stockpiles are useful only for storable and sufficiently standardized inputs. Research alliances, qualification systems, recycling, standards, and screening act across several layers. No single instrument removes every chokepoint.

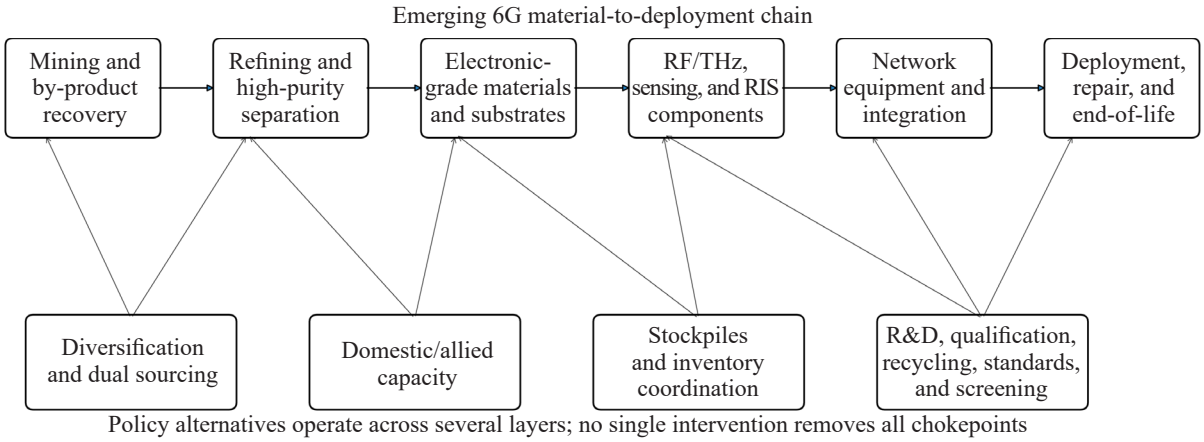


Figure 2. Layered 6G material-to-deployment chain and cross-layer policy alternatives

The distinction between layers also prevents a common empirical error. The United Nations Commodity Trade Statistics Database (UN Comtrade) reports bilateral trade flows under specified customs codes [52]. These flows can inform concentration screening but do not identify the technological grade, production-stage origin or supplier qualification needed to infer 6G-specific dependence. Trade through an intermediary may appear to diversify origin while leaving upstream processing unchanged. USGS statistics are authoritative for mine production and selected processing baselines [10], yet proprietary high-purity conversion and qualification are not always observable. Policy targets under the European Union (EU) Critical Raw Materials Act similarly represent planned benchmarks, not achieved capacity [53]. The European framework is nevertheless informative because it integrates strategic projects, monitoring, stockpiles, circularity, substitution, and a goal that no single third country should account for more than 65% of annual consumption of a strategic raw material at a relevant processing stage. The architecture of the regulation reinforces the argument that resilience depends on a portfolio rather than on extraction

alone. Quantitative supply-chain visibility research further shows that the benefit of greater visibility depends on the network tier and demand environment, making the implied improvement conditional rather than automatic [54].

2.2 Resilience as capability, not inventory alone

The cited resilience literature discusses preparation, response, recovery, adaptation and network viability across distinct organizational and supply-network settings [12-19]; the cited sources do not provide a jointly estimated or uniformly operationalized 6G-specific definition. Early work stressed the value of redesigning networks and building flexibility before a shock occurs [12]. Later studies distinguished vulnerability from capability, treating resilience as a balance between exposure and the resources available to absorb or adapt [14-15]. Firm-level research connects relevant organizational resources and disruption-response capabilities to observed resilience outcomes, within the samples and constructs of those studies [16-17]. Relational competence and cross-organizational coordination also matter because suppliers and buyers often need to exchange information and change processes during a disruption [18]. The viability perspective extends this logic beyond returning to a pre-shock state: intertwined supply networks may need to survive structural change rather than merely recover from a temporary interruption [19]. A recent semiconductor-focused systematic review draws a similar distinction among disruption types, risk-management capabilities and implementation conditions; it should not be read as a direct estimate of 6G policy effectiveness [55].

The resilience literature therefore cautions against treating inventories as the universal answer. Inventory buys time, but it cannot by itself create technical substitutes, new process knowledge, common testing, or additional capacity. It may also be poorly suited to fast-changing components, short shelf lives, or inputs whose value depends on current specifications. Conversely, a qualification system has little visible physical capacity, yet it can shorten the time needed to move from an announced alternative to a usable supplier. Visibility and traceability can appear administrative rather than material, but without them policymakers cannot know whether a second-tier supplier remains dependent on the same upstream processor. The value of an intervention must be judged by the capability it creates and the layer it addresses.

Production-network research explains why these distinctions matter at the macro level. Network position can transmit local disruptions to distant firms, especially where inputs are difficult to substitute [21-22]. Input specificity magnifies the effect of supplier shocks [23]. Evidence from the 2011 Tōhoku earthquake addresses distinct transmission channels: disruption to U.S. affiliates dependent on imported Japanese inputs [24] and propagation through domestic supplier–customer networks in Japan [25]. Those estimates are network- and setting-specific; neither measures commercial 6G disruption losses. Baldwin and Freeman similarly emphasize that global supply-chain risk arises from exposure, propagation, and the speed of adjustment rather than from trade openness by itself [20]. For 6G, the relevant object is thus not "dependence on imports" in the abstract. It is dependence on inputs, processes, equipment, knowledge, or certification nodes whose interruption cannot be absorbed before downstream production is impaired. A contemporary review of geopolitical supply-chain disruptions documents heterogeneous disruption mechanisms and managerial responses, reinforcing the need to avoid universal cost or retaliation claims [56].

Critical-material studies add a specific warning about midstream concentration. Rare-earth supply chains have been shaped by processing capability, environmental costs, and industrial policy, not only by geological endowment [26-29]. National strategies have combined diversification, stockpiles, recycling, substitution, and domestic capacity, with different trade-offs across regions [27]. Analysis of Chinese policy shows that interventions at multiple points of the chain can alter both short-term availability and long-term investment incentives [28]. A resilience framework developed from the 2010 rare-earth crisis emphasizes diversity, flexibility, stockpiling, recycling, and information across the material lifecycle [29]. These lessons transfer to the emerging 6G ecosystem, but they should not be transferred mechanically. The importance of a material is conditional on device architecture and qualification; the policy model must preserve that uncertainty. Recent rare-earth assessments and cross-economy critical-mineral policy frameworks favor differentiated, processing-aware interventions; their examples concern specific minerals and jurisdictional positions, not a settled 6G bill of materials [57-58]. A 2024 mapping of rare-earth recycling trade illustrates how circular-material flows have distinct network geographies, while research on terbium supply identifies environmental regulation and mining technique as important, mineral-specific constraints [59-60]. A contemporary review of rare-earth magnets similarly describes processing, sustainability and geopolitics as interacting challenges in that specific industry [61]. None establishes a required 6G magnet or mineral demand profile.

International political economy further complicates the decision. Studies of bilateral trade after official Dalai Lama meetings [30] and of trade within political-military alliances [31] address bounded political-commercial relationships. Farrell and Newman [32] examine how domestic institutions shape cross-border interdependence and specify the jurisdictional and institutional requirements for the panopticon and chokepoint effects of asymmetric economic networks [33]. Drezner's [34] analysis of creditor power identifies limits to turning financial dependence into political compellence. These studies do not quantify 6G export-control costs or establish a universal retaliation effect. A policy that simply reduces direct trade with one

country can increase costs without changing the underlying processing node. The appropriate objective is a reduction in usable vulnerability, not a politically attractive change in headline trade shares.

2.3 Criteria for policy evaluation

The decision model uses twelve criteria. All are expressed as benefit criteria, so a higher score indicates better policy performance. This common orientation avoids sign errors in TOPSIS while retaining substantive trade-offs in the definitions.

C1, supply-continuity gain, measures the expected reduction in the probability, duration, and downstream severity of interruption. It is not a measure of how visible a policy appears. Continuity depends on concentration, storable inventory, switching time, and the criticality of the affected layer.

C2, substitutability and qualification gain, captures the capacity to replace a material, supplier, process, or component without unacceptable loss of performance, yield, reliability, or interoperability. Nominal supplier availability does not count as substitution until testing and qualification are complete.

C3, domestic and allied capacity gain, covers commercially usable extraction, refining, electronic-grade preparation, substrates, components, laboratories, test infrastructure, repair, and other capabilities that reduce persistent chokepoints. Announced projects are not treated as capacity unless financing, permitting, construction, commissioning, and qualification are plausible.

C4, visibility and traceability gain, concerns multi-tier mapping, origin and processing information, auditable inventories, incident reporting, and early warning. The criterion is expected to exert causal influence because poorly observed dependencies weaken nearly every other intervention. Recent research on supply-chain mapping supports information quality as an organizational enabling capability, although its estimates were not used to set the C4 DEMATEL score here [62].

C5, implementation speed, measures the time until exposure is reduced in practice. It distinguishes a legal announcement from operational effect. A stockpile may act quickly if specifications and release rules exist; a refinery may take years; a common qualification platform may accelerate switching after laboratories and recognition arrangements are operating.

C6, cost-effectiveness, compares resilience gain with fiscal expenditure, compliance cost, price premiums, carrying cost, remediation, and opportunity cost. It is not a preference for the cheapest intervention. High expenditure can be justified where it addresses a severe and persistent bottleneck that cheaper instruments cannot resolve.

No observed commercial 6G supply chain yet exists from which to estimate a project-level monetary loss function for a realized 6G material disruption. Criterion C6 therefore does not import a fictitious 6G cost estimate. Its directional logic is bounded by production-network evidence on propagation and by semiconductor disruption studies documenting how capacity constraints, long lead times, tiered dependencies, and shortage-driven production interruptions generate downstream costs [23-25, 35, 63]. The model uses that evidence to compare relative cost-effectiveness mechanisms; local fiscal appraisal would still require jurisdiction- and project-specific cost data.

C7, innovation and standards compatibility, evaluates whether a policy preserves technical experimentation, interoperability, and participation in the evolving 6G standardization process. Prematurely locking in one architecture can produce stranded capacity, whereas joint testbeds and common qualification can broaden the set of technically viable suppliers.

C8, geopolitical-risk reduction, considers exposure to coercion, retaliation, alliance disagreement, extraterritorial regulation, and abrupt policy reversal. It evaluates the net change in vulnerability rather than the amount of trade shifted away from a named country.

C9, environmental and circularity compatibility, includes lifecycle emissions, energy and water use, waste, recovery, permitting, and community acceptance. Environmental compatibility affects both the legitimacy and the implementation time of new capacity. A lifecycle comparison of rare-earth magnet recycling routes documents technology-dependent environmental consequences; this evidence supports retaining environmental compatibility as a criterion, not assigning any 6G-specific lifecycle score [64].

C10, administrative feasibility, covers legal authority, interagency coordination, technical expertise, procurement capacity, monitoring, enforcement, and compatibility with trade obligations. Policies that require granular end-use controls or multi-tier traceability can underperform when agencies lack usable data and staff.

C11, scalability across layers and firms, asks whether an intervention can expand beyond a small pilot or a few large firms. A technically strong instrument may have limited systemic value if smaller suppliers cannot participate or if each component requires an entirely separate institution.

C12, durability of dependence reduction, measures whether an intervention changes the structure of vulnerability rather than postponing it. Durable policies create knowledge, qualified alternatives, commercially viable capacity, circular flows, or adaptive institutions that remain useful as technology changes.

Table 1 summarizes the criteria, the principal evidence indicators, and the orientation used in TOPSIS. The definitions are deliberately non-overlapping. Continuity is an outcome; substitutability is an adjustment capability; capacity is a physical and organizational resource; visibility is an informational capability; durability measures persistence. Keeping those distinctions clear is essential because DEMATEL estimates influence rather than similarity. Kabir and colleagues [65] use Delphi and Grey-

DEMATEL to examine relationships between supply-chain mapping attributes and performance indicators. Their application is methodologically relevant but does not validate the 6G-specific criterion relationships or ordinal scores used here.

Table 1. Resilience criteria and operational boundaries

Code	Criterion	Dimension	Operational boundary	Orientation
C1	Supply-continuity gain	Operational resilience	Probability, duration, and downstream severity of interruption	Benefit
C2	Substitutability and qualification gain	Technical adaptability	Ability to replace a material, supplier, process, or component after validation	Benefit
C3	Domestic and allied capacity gain	Industrial capability	Commercially usable capacity across processing, materials, components, test, and repair	Benefit
C4	Visibility and traceability gain	Information capability	Multi-tier mapping, origin, processing, inventories, incident reporting, and early warning	Benefit
C5	Implementation speed	Temporal performance	Time from adoption to effective reduction of exposure	Benefit
C6	Cost-effectiveness	Economic performance	Resilience gain relative to fiscal, compliance, carrying, and opportunity costs	Benefit
C7	Innovation and standards compatibility	Technology governance	Preservation of experimentation, interoperability, and standards participation	Benefit
C8	Geopolitical-risk reduction	Strategic exposure	Net reduction in coercion, retaliation, alliance, and policy-reversal exposure	Benefit
C9	Environmental and circularity compatibility	Sustainability	Lifecycle effects, recovery, permitting, and community acceptance	Benefit
C10	Administrative feasibility	Institutional capacity	Legal authority, coordination, expertise, monitoring, procurement, and enforcement	Benefit
C11	Scalability across layers and firms	System reach	Ability to expand beyond pilots and large firms across relevant layers	Benefit
C12	Durability of dependence reduction	Long-run resilience	Persistence and adaptability of the reduction in structural vulnerability	Benefit

2.4 Policy alternatives

The seven alternatives are policy packages rather than isolated legal acts. The base scenario is a medium-sized advanced economy with a substantial telecommunications and semiconductor user base, limited upstream mineral self-sufficiency, and strong allied relationships. The scenario is intended to represent economies that cannot reproduce the entire chain domestically but possess enough technical and market capacity to influence supplier behavior.

A1, multi-sourcing and geographic diversification, combines supplier-development grants, dual-sourcing requirements, trade facilitation, and long-term contracts. The package broadens the supplier base but receives credit only where alternative sources are independently capable and qualified. Rerouting trade through an intermediary without changing upstream processing does not constitute genuine diversification.

A2, domestic and allied refining or component capacity, uses capital support, project finance, tax incentives, workforce development, procurement, and offtake commitments to create commercially usable capacity. Its expected strength is durability; its weaknesses are capital intensity, permitting delay, scale risk, and the possibility of subsidizing capacity that becomes obsolete.

A3, strategic stockpiles and inventory coordination, creates public or pooled reserves with rotation and release rules. It can bridge licensing delays, sudden demand, and short disruptions. It is less suitable for rapidly changing components or materials whose specifications, purity, or storage conditions are unstable.

A4, joint research, standards, and testbed alliances, funds shared research infrastructure, pre-competitive development, interoperability testing, and standards participation. It broadens design options and reduces the chance that resilience policy locks in an obsolete

architecture. Its short-run continuity contribution is lower because research does not automatically create production capacity.

A5, recycling, recovery, and material substitution, supports collection, recovery, high-purity recycling, design for circularity, and alternatives to concentrated inputs. It can improve durability, bargaining power, and environmental performance. Near-term volume may be limited by feedstock availability and stringent purity requirements. Evidence from rare-earth magnet recycling suggests that collection, information, economic incentives, cross-border logistics and certification jointly constrain recovered supply; transferring the lesson to 6G remains conditional on material and purity requirements [66]. Material-flow mapping of UK permanent magnets illustrates persistent information gaps in recoverable stocks [67]. A modelling study of recycling systems in Italy and a regional rare-earth circularity analysis highlight scale, infrastructure and long-horizon constraints on secondary supply [68-69]. Contemporary policy commentary also stresses the institutional coordination required to improve rare-earth recycling [70]; these examples concern other end uses and do not quantify recoverable 6G feedstock.

A6, shared supplier qualification and certification platforms, pools testing, recognizes results across firms or allied jurisdictions, standardizes evidence, and reduces duplicate qualification costs. The package targets the gap between a nominal alternative and a supplier that network-equipment and component firms can actually use. Its governance must remain open and reviewable, because a closed recognition system could create a new chokepoint. Recent supplier-selection research demonstrates an alternative hybrid weighting design under subjective judgments; it does not validate the performance values assigned to A6 in this study [71].

A7, selective export control, investment screening, and supply-risk review, protects sensitive capabilities and identifies strategic exposure. The package is narrowly defined and subject to review. Broad controls may invite retaliation, fragment standards, reduce learning, and raise costs; the package is therefore assessed as a complement to positive capability-building rather than as a substitute for it.

Table 2 records the core mechanism and principal limitation of each alternative. The distinction between alternatives is analytical, not mutually exclusive. The final policy recommendation can combine packages across different time horizons.

Table 2. Policy alternatives evaluated in the model

Code	Policy package	Core mechanism	Principal limitation
A1	Multi-sourcing and geographic diversification	Supplier development, dual sourcing, trade facilitation, and long-term contracts	May reroute trade without changing upstream concentration
A2	Domestic and allied refining/ component capacity	Capital support, project finance, procurement, skills, and offtake	High cost, permitting delay, scale risk, and possible obsolete capacity
A3	Strategic stockpiles and inventory coordination	Public or pooled reserves, rotation, and release protocols	Temporary insurance; weak for changing components and prolonged scarcity
A4	Joint R&D, standards, and testbed alliances	Shared research, interoperability testing, standards, and pre-competitive development	Research does not guarantee near-term production
A5	Recycling, recovery, and material substitution	Collection, high-purity recovery, design for circularity, and substitution R&D	Feedstock, purity, and scale constrain near-term supply
A6	Shared supplier qualification and certification platforms	Pooled testing, mutual recognition, common evidence, and supplier onboarding	Closed governance can create a new recognition or data chokepoint
A7	Selective export control, investment screening, and risk review	Narrow controls, screening, licensing, and periodic review	Retaliation, fragmentation, compliance cost, and reduced learning

3. Materials and methods

3.1 Research design and evidence base

The study uses an evidence-calibrated hybrid DEMATEL–TOPSIS design. Here, 'evidence-calibrated' means that ordinal judgments are anchored to explicit, traceable source-based rules; it does not mean statistical calibration, stakeholder consensus, or measurement without analyst judgment. The approach was selected because the 6G hardware ecosystem is pre-commercial and because a verified cross-national panel of procurement, engineering, material, and policy experts was not available for the present analysis. Rather than invent expert responses or infer preferences from the desired conclusion, the model relies on a structured

coding protocol applied to publicly verifiable sources. It should therefore be read as a transparent decision-analysis synthesis and benchmark for later validation, not as a survey of stakeholder preferences.

The evidence cut-off was 1 August 2026. The substantive corpus contained 35 records: four official data or policy sources and 31 peer-reviewed studies. The official sources were International Telecommunication Union Radiocommunication Sector (ITU-R) Recommendation M.2160, USGS Mineral Commodity Summaries 2026, the EU Critical Raw Materials Act, and the UN Comtrade database [1, 10, 52-53]. The peer-reviewed corpus covered 6G technology [2-8], supply-chain resilience and semiconductor disruption [12-20, 35], production-network propagation [21-25], critical-material supply chains [26-29], and international interdependence, creditor influence, diplomacy-linked exports, and alliance-related trade [30-34]. Nine methodological studies specified the DEMATEL, TOPSIS, and hybrid MCDM procedures [37-45]. Commodity concentration is interpreted within the reporting scope of the USGS 2026 summaries [10]. Contextual literature, including recent AI-oriented 6G surveys [72], is distinguished from the 35-record coding corpus and did not contribute to the X or A matrices frozen at the 1 August 2026 cut-off. The bibliography is therefore broader than the source set used to substantiate the assigned ordinal scores.

The literature assembly was a structured, purposive, function-based search rather than a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. It was not intended to estimate a population of studies or claim database exhaustiveness. Sources were retained when they performed at least one of four functions: defined a 6G capability or component pathway; identified a resilience mechanism; documented a production-network, semiconductor, or critical-material bottleneck; or analyzed the implementation effects of a relevant policy instrument. Commentaries without traceable methods, vendor marketing material, and sources that treated a speculative 6G material list as settled were excluded. Official statistics were used for factual boundaries, but a country share or customs code was not translated directly into a policy score without an explicit mechanism. This selective scope is stated explicitly so that the 31 peer-reviewed records are not mistaken for the output of a systematic review.

The unit of analysis in the DEMATEL stage was a directed relation from criterion i to criterion j; in the TOPSIS stage it was the expected performance of policy alternative a on criterion j. A coding memorandum was prepared for every non-zero DEMATEL entry and every TOPSIS score. Because these matrices are the empirical core of the model, Supplementary Workbook S1 is treated as essential replication material rather than an optional appendix. The workbook uses clearly named tabs corresponding to the notation in this section: S1_X_Direct (12 × 12 direct-influence matrix X), S2_T_TotalRelation (T, D, R, $D + R$, $D - R$), S3_DEMATEL_Memos (rationale and supporting evidence for each non-zero x_{ij}), S4_A_Performance (7 × 12 decision matrix A), S5_TOPSIS_Calculation (normalization, weighted values, ideal solutions, distances, and closeness), S6_ScenarioWeights (complete numeric weight vectors), and S7_Robustness (criterion deletion and stochastic perturbation outputs).

The evidence-coding approach necessarily contains analyst judgment. Criterion definitions and alternative packages were frozen before calculation, and ordinal categories constrained free numerical choice, but the matrices were coded by one analyst. No second coder was used and no Cohen's kappa or Fleiss' kappa was calculated; the manuscript therefore does not claim inter-coder reliability or stakeholder validation. To make future replication more disciplined, Section 3.2 gives explicit evidentiary anchors for scores 0–4. Borderline judgments are to be resolved conservatively in replication: the lower score is assigned unless the evidentiary anchor for the higher category is fully satisfied, and the memo must record the mechanism, boundary condition, and source family. The reported sensitivity tests address weight sensitivity within the coded model; they do not remove single-coder measurement uncertainty.

3.2 Coding the DEMATEL direct-influence matrix

Each off-diagonal criterion pair was coded on a five-point DEMATEL scale from 0 to 4. Diagonal entries were fixed at zero, and the coding target was direct or enabling influence rather than correlation, desirability, conceptual similarity, or policy importance. Table 3 states explicit replication anchors for each score. The key distinction between 2 and 3 is evidentiary breadth: a score of 2 requires one clearly specified direct mechanism with independent corroboration, whereas a score of 3 requires the same directional mechanism to be supported across multiple independent studies, source families, or settings with no material contradiction in the coded corpus. A score of 4 is reserved for repeatedly documented cross-context mechanisms and is therefore intentionally difficult to assign.

Table 3. Anchored replication rubric for DEMATEL direct-influence coding

Score	Label	Replication anchor
0	No supported direct influence	No traceable direct mechanism in the retained evidence; only correlation, conceptual similarity, or an unsupported assertion
1	Limited/conditional	A plausible direct mechanism is documented in one source or one narrow setting, but it is strongly conditional, weakly corroborated, or not readily transferable
2	Moderate	One explicit directional mechanism is supported and independently corroborated by at least one additional record or source family; boundary conditions are identifiable
3	Strong	The same directional mechanism is supported across multiple independent studies, source families, or settings; relevance is consistent and no material contradiction appears in the coded corpus
4	Very strong	The mechanism is repeatedly documented across three or more independent source families or settings, is directly relevant across applicable contexts, and shows consistent directional support

Replication rule for borderline cases: assign the lower category unless the higher-category anchor is fully satisfied; record the mechanism, boundary condition, and supporting source family in S3_DEMATEL_Memos. This rule improves auditability but does not retroactively create inter-coder agreement for the original single-coder matrices

The coding logic can be illustrated without equating influence with preference. A visibility-to-implementation-speed score reflects the mechanism by which multi-tier mapping and usable incident information permit agencies and firms to target intervention more quickly; the reverse relation is weaker because faster implementation does not necessarily improve information quality. A substitutability-to-continuity score captures how technically qualified alternatives shorten interruption, whereas administrative-feasibility-to-capacity captures the dependence of projects on permitting, financing, coordination, and procurement. The sign of a policy consequence is interpreted in the memo; the 0–4 value records the strength of the directed relation, not whether the relation is normatively desirable. Recent research on explainable TOPSIS motivates the explicit separation between influence structure, normative weights and the geometry of final alternative rankings [73].

Let $X = [x_{ij}]$ denote the 12 × 12 direct-influence matrix. The normalization scalar was:

$$s = \max\left\{\max_i \sum_j x_{ij}, \max_j \sum_i x_{ij}\right\}. \quad (1)$$

The normalized direct-relation matrix was calculated as follows; the total-relation matrix was then obtained by summing direct and indirect effects:

$$N = \frac{X}{s}, \quad (2)$$

$$T = N(I - N)^{-1}. \quad (3)$$

For criterion i, dispatched influence was $D_i = \Sigma_j t_{ij}$, and received influence was $R_i = \Sigma_j t_{ji}$. Prominence, $D_i + R_i$, measures how deeply the criterion is embedded in the system. Relation, $D_i - R_i$, identifies whether the criterion is a net cause or a net effect. A positive value places the criterion in the causal group; a negative value places it in the effect group. The criterion weight used in the baseline TOPSIS model was normalized prominence:

$$w_i = \frac{D_i + R_i}{\sum_k (D_k + R_k)}. \quad (4)$$

Normalized prominence is used here as a structural-salience baseline, not as a claim that $D + R$ is identical to normative importance. $D + R$ measures how strongly a criterion is embedded in the influence system, while $D - R$ indicates whether it is a net dispatcher or receiver of influence. Using only $D - R$ as a weight would systematically down-weight outcome criteria such as continuity or durability simply because they receive influence. The baseline therefore uses normalized $D + R$ to retain systemically central causes and effects, reports $D - R$ separately for implementation sequencing, and tests equal and policy-preference weights to show how rankings change when normative emphasis differs from structural salience. This distinction is central to the hybrid architecture: DEMATEL supplies a transparent structural baseline; TOPSIS performs the compensatory alternative ranking; scenario weights represent preference choices rather than being inferred from the causal network. The inverse in equation (3) is evaluated only when the normalized direct-relation matrix has a spectral radius below one; this numerical precondition must be checked against the supplied raw matrix in Supplementary Workbook S1.

A worked aggregation example uses C4 (visibility and traceability). From the total-relation matrix, its dispatched influence is $D_4 = 2.974$ and its received influence is $R_4 = 1.148$, so prominence is $D_4 + R_4 = 4.122$ and net relation is $D_4 - R_4 = 1.826$. The sum of all twelve prominence

values is 56.829; therefore the baseline TOPSIS weight is $w_4 = 4.122/56.829 = 0.0725$, reported as 0.073 in Table 4. The individual t_{4j} and t_{j4} entries generating D_4 and R_4 are reported in S2_T_TotalRelation, with the corresponding raw x_{4j} judgments and evidence memoranda in S1_X_Direct and S3_DEMATEL_Memos.

The mean non-diagonal value of T was 0.202 and was used only as an edge-display rule when presenting directed relations from T. It does not enter the weights, TOPSIS calculations, or coordinates of the cause–effect scatter. Because Figure 3 plots D + R against $D - R$ rather than individual t_{ij} edges, 0.202 is not an axis threshold and no vertical or horizontal threshold line is mathematically appropriate. Figure 3 therefore states the threshold in an annotation and labels both axes as dimensionless sums derived from the normalized total-relation matrix.

Table 4. DEMATEL results for the twelve resilience criteria

Code	Criterion	D	R	$D + R$	$D - R$	Weight
C1	Supply-continuity gain	1.225	2.650	3.875	-1.425	0.068
C2	Substitutability and qualification gain	2.227	2.324	4.551	-0.097	0.080
C3	Domestic and allied capacity gain	2.721	2.956	5.676	-0.235	0.100
C4	Visibility and traceability gain	2.974	1.148	4.122	1.826	0.073
C5	Implementation speed	1.557	2.580	4.138	-1.023	0.073
C6	Cost-effectiveness	2.076	3.002	5.078	-0.926	0.089
C7	Innovation and standards compatibility	2.831	1.696	4.527	1.135	0.080
C8	Geopolitical-risk reduction	2.821	2.317	5.138	0.503	0.090
C9	Environmental and circularity compatibility	2.106	1.601	3.706	0.505	0.065
C10	Administrative feasibility	2.724	2.269	4.993	0.456	0.088
C11	Scalability across layers and firms	2.598	2.603	5.201	-0.006	0.092
C12	Durability of dependence reduction	2.556	3.269	5.825	-0.713	0.103

Note: $D = \Sigma_j t_{ij}$ (dispatched influence); $R = \Sigma_j t_{ji}$ (received influence). $D + R$ measures structural prominence; $D - R$ identifies net cause/effect status. All four quantities are dimensionless because they are derived from the normalized total-relation matrix T. For cross-file consistency, all displayed DEMATEL values are recalculated from the S1_X_Direct matrix and reported from S2_T_TotalRelation at full precision; rounding is applied only for presentation

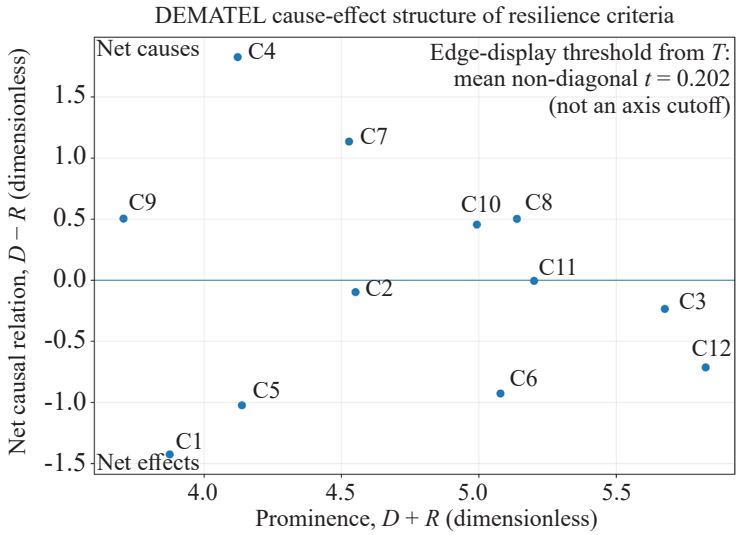


Figure 3. DEMATEL cause–effect map of the resilience criteria. Axes are dimensionless sums from the normalized total-relation matrix; mean non-diagonal $t_{ij} = 0.202$ is an edge-display threshold, not an axis cutoff

3.3 Coding and calculating TOPSIS

Each policy alternative was evaluated against the twelve criteria on a nine-point scale. Scores of 1, 3, 5, 7, and 9 represented very weak, weak, mixed, strong, and very strong expected performance; 2, 4, 6, and 8 represented intermediate assessments. A score represented performance under the base scenario, not the intrinsic importance of the criterion. The coding memo required an explicit mechanism, a recognized limitation, and at least one source family consistent with the assessment.

The procedure produced a 7 × 12 decision matrix $A = [a_{ij}]$: the seven rows correspond to policy alternatives A1–A7, the twelve columns correspond to criteria C1–C12, and each cell a_{ij} is the 1–9 performance score assigned to policy i on criterion j. Because all criteria are formulated as benefits, higher values consistently indicate more desirable performance. The complete matrix and the evidence memo for every cell are designated for S4_A_Performance and the accompanying coding documentation. Vector normalization was specified as part of the present TOPSIS model: each entry is divided by the Euclidean norm of the seven alternatives' scores for that criterion. This is a transparent scaling choice for the common 1–9 benefit scale, not an empirical finding that this scaling is superior. Opricovic and Tzeng [38] compare the compromise logic of VIKOR and TOPSIS, and Behzadian et al. [39] catalogue TOPSIS applications and methodological variants; neither provides a test showing that vector normalization preserves policy rankings under alternative scaling rules. This choice is not assumed to be innocuous: a separate min–max normalization comparison was not performed here and remains a model-choice limitation. Shyur and Shih [74] analyze TOPSIS rank reversal for min–max and max normalization combined with Euclidean, Manhattan, and Chebyshev distances. Their analysis does not test vector normalization or the policy matrix reported here. Bánhidi and Dobos [75] compare TOPSIS normalization and weighting choices in a digital-development dataset, while Roszkowska [76] examines normalization and entropy-based weighting in a broader MCDA setting. These findings establish specific examples of methodological sensitivity, not invariance or instability of the present results. The weight sensitivity tests in this article therefore do not certify robustness to different normalization rules.

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_k a_{kj}^2}}. \tag{5}$$

The weighted normalized matrix was $v_{ij} = w_j r_{ij}$ (with index i denoting alternatives and j denoting criteria). The positive ideal solution V^+ contained the maximum v_{ij} for every criterion, and the negative ideal solution V^- contained the minimum. The Euclidean distances were:

$$S_i^+ = \sqrt{\sum_j \left(v_{ij} - v_j^+\right)^2}, \tag{6}$$

and

$$S_i^- = \sqrt{\sum_j \left(v_{ij} - v_j^-\right)^2}. \tag{7}$$

The closeness coefficient was:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}. \tag{8}$$

Alternatives were ranked from the highest C_i to the lowest. The coefficient is comparative within the defined decision matrix and lies between 0 and 1 because it is a relative-distance ratio; it is not a probability of policy success or an absolute performance scale. For A6, S5_TOPSIS_Calculation gives $S^+ = 0.018591$ and $S^- = 0.082192$, yielding a full-precision closeness coefficient of 0.815532, which is reported as 0.816 in the manuscript. The value is therefore 'high' only in the geometric sense that A6 lies nearer to the positive ideal and farther from the negative ideal than the other alternatives under this matrix and weight profile. It should not be translated into an 81.6% success claim.

3.4 Robustness tests

Four forms of sensitivity analysis were conducted. First, the baseline prominence weights were replaced with equal weights. Second, four policy-preference scenarios were specified while holding the performance matrix fixed: the security-first scenario increases emphasis on continuity, domestic/allied capacity, geopolitical-risk reduction, and durability (C1, C3, C8, C12); the speed-and-administrative-feasibility scenario emphasizes C5 and C10; the cost-control scenario emphasizes C6; and the green-transition scenario emphasizes environmental/circularity compatibility and durability (C9, C12). The complete numeric vectors, each normalized to sum to one, are reported in S6_ScenarioWeights so that the redistribution is numerically reproducible rather than left as a verbal description. Third, each criterion was removed in turn and the remaining weights were renormalized, producing twelve leave-one-criterion-out rankings. Fourth, 10,000 stochastic weight vectors were generated by multiplying each baseline weight by an independent lognormal perturbation with standard deviation 0.20 and renormalizing the result; rank frequencies were then recorded. Recent full-range sensitivity work distinguishes local perturbation robustness from coverage of the entire admissible weight simplex; the present 10,000 draws address only the former [77].

The sensitivity analysis focuses on weights because they are an explicit source of contestability in a document-coded model. Performance scores were also inspected for dominance and close rankings, but no alternative dominated all others across every criterion. The stochastic exercise should therefore be interpreted as weight-robustness conditional on the fixed coded performance matrix, not as a sampling distribution or statistical confidence interval. The supplementary workbook is designed to allow a reader to change scores and recalculate results, but the present article does not claim invariance to alternative normalization rules, alternative uncertainty formalisms, or independent recoding.

3.5 Research integrity and reproducibility

No human participants, personal data, interviews, or confidential firm data were used. Institutional review approval was therefore not required. No external expert or stakeholder validation exercise was conducted, and the matrices should not be interpreted as the preferences of governments, engineers, or industry. This limitation is stated explicitly rather than replaced with a post hoc validation claim. Reproducibility in the present design means computational auditability: a reader with the complete S1 workbook can inspect the direct matrix, performance matrix, coding memoranda, scenario weights, formulas, and robustness outputs and can recalculate the reported results. External validity still requires independent coders and/or a stakeholder panel.

4. Results

4.1 DEMATEL causal structure and criterion weights

The maximum row or column sum of the direct matrix was 38, which was used as the normalization scalar. The mean non-diagonal total-relation value was 0.202. Table 4 reports D (the row sum of T, or dispatched influence), R (the column sum of T, or received influence), prominence $D + R$, net relation $D - R$, and normalized prominence weight for all twelve criteria. Because X is normalized before constructing T, D, R, $D + R$, and $D - R$ are dimensionless influence indices rather than physical units.

Five criteria formed the net-causal group. Visibility and traceability (C4) had the largest positive relation value, $D - R = 1.826$. Innovation and standards compatibility (C7) followed at 1.135. Environmental and circularity compatibility (C9), geopolitical-risk reduction (C8), and administrative feasibility (C10) had positive relation values of 0.505, 0.503, and 0.456, respectively. The remaining criteria were net effects. Supply continuity (C1) had the most negative relation value, −1.425, followed by implementation speed (C5), −1.023, and cost-effectiveness (C6), −0.926. Durability (C12) was also an effect criterion, −0.713, despite receiving the highest prominence weight.

Figure 3 separates causal leverage from systemic prominence. The horizontal axis is $D + R$ and the vertical axis is $D - R$; both are dimensionless sums from the normalized total-relation matrix. Visibility occupies the upper-left portion of the map: it is a strong net cause but has only moderate prominence. Durability lies at the far right and below the horizontal axis: it is the most systemically embedded criterion but is produced by the configuration of other capabilities. Capacity (C3) and scalability (C11) also have high prominence and small or negative relation values, indicating that they are central outcomes and transmission mechanisms rather than first-order levers. The 0.202 mean non-diagonal t_{ij} threshold concerns which directed edges are displayed from T and is annotated on the figure; it is not a coordinate threshold on this $D + R/D - R$ scatter.

The prominence weights reinforce this interpretation. Durability received 0.103, domestic and allied capacity 0.100, scalability 0.092, geopolitical-risk reduction 0.090, cost-effectiveness 0.089, and administrative feasibility 0.088. Substitutability received 0.080, innovation compatibility 0.080, implementation speed 0.073, visibility 0.073, continuity 0.068, and environmental compatibility 0.065. The weights are relatively dispersed; none exceeds 0.11. The result does not support a model in which one factor overwhelms the rest.

The strongest total-relation pathways converged on durability. Innovation compatibility → durability was 0.330; geopolitical-risk reduction → durability was 0.330; administrative feasibility → durability was 0.322; capacity → durability was 0.321; and visibility → durability was 0.319. Other strong pathways included geopolitical-risk reduction → cost-effectiveness (0.312), scalability → durability (0.311), innovation compatibility → cost-effectiveness (0.311), capacity → cost-effectiveness (0.306), administrative feasibility → cost-effectiveness (0.306), and visibility → continuity (0.302). These pathways show why durable resilience cannot be obtained by a single procurement or trade measure. It emerges from information, administrative capability, adaptable technology, feasible capacity, and the ability to scale.

The placement of geopolitical-risk reduction in the causal group requires careful interpretation. It does not imply that geopolitical tension is a controllable policy instrument. The coding reflects the way a reduction in exposure to coercion or policy reversal changes investment, cost, and capacity choices. At the same time, the criterion is influenced by capacity, substitutability, and visibility through the total-relation matrix. DEMATEL identifies net direction within the coded system, not a claim of unilateral political control.

4.2 TOPSIS ranking of policy alternatives

Table 5 reports each alternative's closeness coefficient and rank; the full-precision S^+ and S^- distances are reported

in S5_TOPSIS_Calculation. Shared supplier qualification and certification platforms (A6) ranked first with C = 0.816. Joint research, standards, and testbed alliances (A4) ranked second at 0.637. Recycling, recovery, and substitution (A5) ranked third at 0.576, narrowly ahead of multi-sourcing and geographic diversification (A1) at 0.574. Domestic and allied capacity (A2) ranked fifth at 0.500. Strategic stockpiles (A3) ranked sixth at 0.363, and selective controls and screening (A7) ranked seventh at 0.285. The magnitude of a closeness coefficient is interpreted only relative to the ideal solutions generated by this decision matrix; no standardized external threshold defines 0.816 as 'substantial'.

Table 5. Baseline TOPSIS ranking of policy alternatives (full-precision distances are reported in S5_TOPSIS_Calculation)

Rank	Code	Policy package	Closeness
1	A6	Shared supplier qualification and certification platforms	0.816
2	A4	Joint R&D, standards, and testbed alliances	0.637
3	A5	Recycling, recovery, and material substitution	0.576
4	A1	Multi-sourcing and geographic diversification	0.574
5	A2	Domestic and allied refining/component capacity	0.500
6	A3	Strategic stockpiles and inventory coordination	0.363
7	A7	Selective export control, investment screening, and risk review	0.285

Figure 4 shows the baseline numerical separation among alternatives. A6 exceeds A4 by 0.179 within the stated matrix and weighting profile, which is the largest adjacent gap in the baseline ranking. This is a descriptive geometric separation, not a standardized effect size. By contrast, A5 exceeds A1 by only 0.002. Because TOPSIS coefficients here are deterministic functions of coded inputs rather than estimates from a random sample, a conventional p-value or significance test is not defined for that gap. The appropriate evidence is sensitivity: A5 and A1 change order across alternative preference profiles. They are therefore described as a preference-sensitive middle cluster rather than as statistically distinguishable ranks.

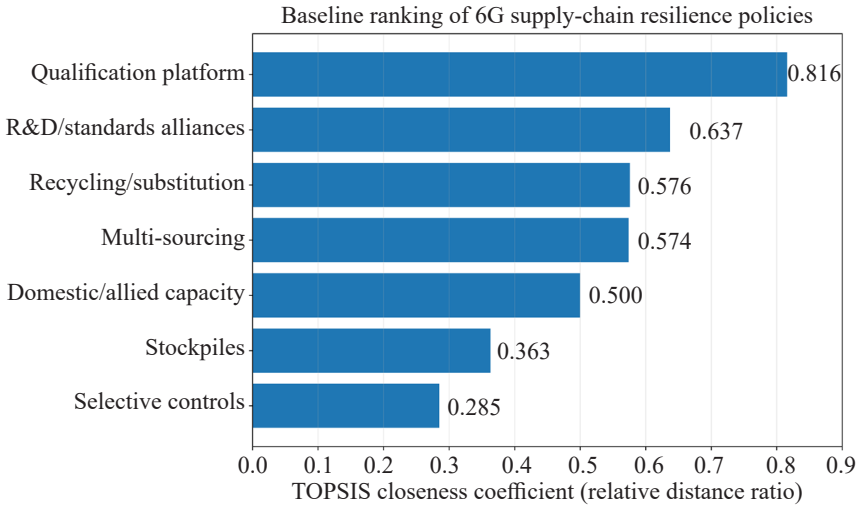


Figure 4. Baseline TOPSIS ranking of 6G supply-chain resilience policy packages

A6 scored strongly because it performed well across both causal and high-prominence criteria. It improves visibility by standardizing supplier information, substitutability by reducing duplicated testing, implementation speed

by shortening qualification, innovation compatibility by using common and revisable test protocols, administrative feasibility by creating a reusable institutional process, and scalability by allowing several firms or jurisdictions to rely on recognized results. It does not eliminate upstream concentration, but it makes diversification and capacity policy more usable.

A4 ranked second because joint research and standards alliances preserve options under architectural uncertainty. The package scored particularly well on substitutability, visibility, innovation compatibility, scalability, and durability. Its lower continuity and speed scores reflect the time required for research and the absence of guaranteed production. A5 and A1 formed a near-tie. Recycling and substitution offered strong environmental, substitutability, geopolitical, and durability performance but weaker short-term speed. Diversification delivered better speed and cost-effectiveness but could be shallow if the alternate supplier relied on the same processor.

Domestic and allied capacity did not rank fifth because capacity lacks importance. Capacity had the second-highest criterion weight. The package ranked fifth because it combines very strong continuity, capacity, geopolitical, and durability performance with weak speed, cost-effectiveness, environmental compatibility, and administrative feasibility. TOPSIS penalizes that uneven profile. The result supports targeted capacity at diagnosed chokepoints rather than a general instruction to reproduce every layer domestically.

Stockpiles ranked sixth because their short-run speed and continuity advantages did not compensate for weak substitutability, capacity creation, and durability. Selective controls ranked last because the package performed weakly on innovation compatibility, cost-effectiveness, substitution, and durability. Controls may still be necessary for a narrowly defined security objective, but the model does not support treating restriction as the primary resilience strategy.

4.3 Sensitivity and ranking stability

The first-place result was stable under the reported weight perturbations. A6 remained first under equal weights and all four policy-preference scenarios, in every one of the twelve leave-one-criterion-out models, and in all 10,000 stochastic weight perturbations. Its mean closeness coefficient across the perturbations was 0.816 with a standard deviation of 0.015. A4 remained second in every leave-one-criterion-out model; in the stochastic analysis it ranked second in 9,914 runs and third in 86 runs, for a mean rank of 2.01. These results support weight-robustness within the fixed performance matrix; they do not establish robustness to independent recoding, alternative normalization, or a different MCDM formalism.

The middle of the ranking was more sensitive. Under equal weights, A1 moved to third and A5 to fourth. Under the security-first scenario, A1 ranked second (0.574), A2 third (0.572), A4 fourth (0.572), and A5 fifth (0.525); the second-through-fourth positions were therefore tightly clustered. Under the speed and feasibility scenario, A1 ranked second and stockpiles rose to third, while domestic capacity fell to seventh. Under cost control, A1 ranked second, A4 third, and A5 fourth. Under the green-transition scenario, A5 rose to second and A4 remained third.

Table 6 summarizes the scenario rankings. This sensitivity pattern changes the interpretation of the baseline near-tie between recycling and diversification. These alternatives are not substitutes for the same policy objective. Diversification performs better when speed, administrative feasibility, and near-term continuity receive greater weight; recycling and substitution perform better when environmental compatibility and durable dependence reduction receive greater weight. The exact scenario vectors are required in S6_ScenarioWeights so that readers can reproduce the redistributions rather than infer them from the rank table. A decision-maker should therefore disclose the preference profile rather than claim that the difference between ranks three and four is universal.

Table 6. Sensitivity of policy rankings to alternative preference profiles

Scenario	A1	A2	A3	A4	A5	A6	A7
Base DEMATEL	4	5	6	2	3	1	7
Equal weights	3	5	6	2	4	1	7
Security first	2	3	6	4	5	1	7
Speed and feasibility	2	7	3	4	6	1	5
Cost control	2	6	5	3	4	1	7
Green transition	4	5	6	3	2	1	7

The lowest ranks were more stable than the middle. A2 remained fifth in every criterion-deletion model but moved between third and seventh across policy scenarios. A3 remained sixth in the criterion-deletion tests and rose only when speed received a large weight. A7 remained seventh in all criterion-deletion models. In the 10,000 stochastic weight perturbations, A7 ranked seventh in 9,981 runs (99.81%) and sixth in 19 runs (0.19%). These patterns suggest that stockpiles and controls should be evaluated as contingent instruments tied to defined disruption scenarios, not as the default foundation of resilience policy.

5. Discussion

5.1 Qualification infrastructure as the hidden resilience bottleneck

The strongest finding is not that testing institutions are more important than mines, refineries, or semiconductor fabrication in every circumstance. It is that shared qualification infrastructure has the most balanced performance across an uncertain and layered system. Critical-material policy often begins with physical concentration because production shares are measurable and politically salient. Yet a nominally available source does not reduce vulnerability if firms cannot verify its origin, test its performance, redesign around it, or rely on recognized certification. The gap between "another supplier exists" and "another supplier can be used before production stops" is where many diversification strategies fail.

This interpretation is consistent with the supply-chain literature's emphasis on flexibility, relational coordination, and reconfiguration [14-19]. It also follows from production-network research: input specificity increases propagation because firms cannot substitute quickly [23-25]. A qualification platform directly targets specificity by reducing duplicated testing and by making the conditions of substitution more transparent. In the 6G context, where architectures and performance requirements remain open, the platform can be designed as a modular capability. It need not certify a single permanent material pathway. It can maintain test protocols, data schemas, laboratory recognition, and confidential information rules that evolve with standards.

The result also clarifies why visibility is the strongest net cause. Supply-chain mapping is sometimes dismissed as a reporting exercise. In this model, visibility influences continuity, capacity, speed, cost, and durability because information determines where intervention is directed. A government that knows only the country of final import may subsidize the wrong stage. A manufacturer that knows only its first-tier supplier may discover too late that multiple suppliers depend on the same high-purity processor. Shared qualification links information to action: supplier data are collected for a purpose, and the output is a usable switching option rather than a static risk register.

The emphasis on qualification also has a direct procurement and supplier-development basis. Supplier qualification is not costless screening: procurement research shows that qualification decisions interact with sourcing competition and can require explicit trade-offs between screening cost and access to qualified bidders [78]. Supply-market research likewise treats the ability to generate and exploit upstream market intelligence as a dynamic capability for identifying and developing alternative suppliers under technological turbulence [79]. These studies do not prove that a shared 6G platform will eliminate material bottlenecks. They support the narrower mechanism used for A6: reducing duplicated verification and improving information can shorten the path from a nominal alternative to an organizationally usable supplier, conditional on technical equivalence and open governance.

Governance design remains critical. A qualification platform can reproduce concentration if a small coalition controls laboratory access, data standards, or recognition. It can also expose proprietary information and raise fixed costs for smaller firms. The policy package therefore requires transparent entry rules, mutual recognition, protection of confidential data, appeal procedures, periodic review, and support for smaller suppliers. These safeguards are not peripheral; they determine whether the platform increases scalability or becomes a new gatekeeping node.

5.2 A sequence rather than a universal ranking

The DEMATEL map and TOPSIS ranking should be read together. The ranking identifies the package closest to the preferred profile. The causal map identifies capabilities that change the performance of several packages. Combining the two produces a sequence.

The first stage is diagnostic and institutional. Governments and firms establish multi-tier visibility, common evidence requirements, early-warning protocols, and shared qualification capacity. These measures have moderate direct physical effects but high enabling effects. They distinguish genuine diversification from trade rerouting, identify which materials or components are sufficiently standardized for stockpiling, and reveal where additional test or processing capacity is required.

The second stage expands options. Multi-sourcing, joint research, standards participation, and substitution reduce the number of single points of failure. The balance among these instruments depends on the problem. Diversification is suitable where qualified suppliers exist but contracts, finance, or market access constrain entry. Research and testbed alliances are suitable where technical pathways remain uncertain. Substitution is valuable where a material or process is highly concentrated and replacement can be designed before a crisis. Recycling is more important where end-of-life feedstock and high-purity recovery can reach meaningful scale.

The third stage uses capital-intensive or restrictive

instruments selectively. Domestic or allied capacity is justified where the earlier stages identify a persistent and high-consequence chokepoint, where scale is commercially plausible, and where permitting and environmental constraints can be managed. Stockpiles are justified for storable inputs with known specifications and clear release rules. Export controls and screening are justified where a narrowly defined security interest cannot be protected through less disruptive measures. Their use should be reviewable because broad controls may reduce the innovation and standards compatibility that the model identifies as a causal capability.

This sequence is more realistic than a single instruction to "reshore" the chain. A medium-sized economy cannot reproduce every production stage efficiently. Even large markets depend on cross-border knowledge, equipment, and inputs. Resilience is therefore a problem of reducing unmanageable dependence while preserving the scale and learning benefits of specialization. The relevant comparison is not autarky versus vulnerability; it is between alternative configurations of dependence, substitution, and coordinated capacity.

5.3 Why physical capacity is central but not automatically first

Domestic and allied capacity had the second-highest prominence weight but ranked fifth as a policy package. This apparent tension is analytically useful. Criterion prominence measures how strongly capacity is connected to the resilience system. Policy ranking measures the balance of benefits and costs associated with a particular capacity-building package. A criterion can be central while a broad instrument designed to improve it is not the preferred first move.

Capacity projects are exposed to several sources of policy failure. A subsidized plant may target a material pathway that standards later disfavor. Announced capacity may never reach qualified output. Permitting and local opposition can delay operation. Small domestic demand may leave a facility dependent on continuing subsidy. Allied capacity may remain concentrated within one partner. These risks do not negate the value of capacity; they justify sequencing it after visibility, technical validation, and demand aggregation.

This portfolio interpretation is compatible with critical-material research on processing and resilience strategies [26-29], but those studies do not establish that the particular sequence ranked here will succeed in every jurisdiction. Capacity is most durable when supported by offtake, qualified demand, research, skills, environmental performance, and alternative suppliers. In other words, the lower-ranked capacity package can become more effective after the higher-ranked qualification and research packages have reduced uncertainty. This complementarity is one reason the final decision output should be a portfolio rather than a winner-takes-all selection. The policy sequence is consequently offered as a scenario-specific decision implication, not as an empirical generalization from the cited mineral policy cases.

5.4 Stockpiles and controls as scenario-dependent insurance

Stockpiles are politically attractive because they are tangible and can be deployed quickly. Their sixth-place baseline rank does not imply that they are useless. It indicates that their value is concentrated in a narrow function: temporal insurance. When disruption is expected to be short, the input is storable, specifications are stable, and release rules are credible, stockpiles can be indispensable. The speed-and-feasibility scenario moved stockpiles to third place. The package remained weak on substitution and durability, however, because inventory is depleted and may postpone structural adjustment.

The same conditional logic applies to export controls and screening. Fuchs and Klann [30] assess changes in bilateral exports associated with high-level diplomatic encounters in the Dalai Lama setting, whereas Gowa and Mansfield [31] analyze the relationship between alliances and trade openness; neither estimates the effects of export licensing or 6G technology controls. Farrell and Newman explain how jurisdiction over central economic-network nodes can enable monitoring or access denial under specific institutional conditions [33], without estimating whether any prospective 6G component chain has the same topology or coercive leverage. Drezner [34] finds limits to political compellence in the distinct context of creditor dependence; it is not evidence of retaliation in semiconductor supply chains. In this policy model, standards fragmentation, a narrower supplier pool, and duplicated technology stacks are scenario risks attributed to broad controls, not measured outcomes in an operating 6G market. The seventh-place ranking follows from the specified ordinal scores and weights. A narrow control may still be warranted for a specific technology, but it should be accompanied by positive investments in substitution, qualification, and allied capacity. The review of economic coercion and trade politics thus informs a possible mechanism rather than the magnitude, probability or net incidence of a prospective 6G control.

The C8 relations should also be treated as time-stamped rather than structurally permanent. An exogenous geopolitical shock—such as a new export-control regime, sanctions episode, armed conflict, alliance realignment, or abrupt licensing change—can alter both the exposure represented by C8 and the strength of directed relations in X. For example, a new control may increase the influence of substitutability on continuity, raise the administrative burden of diversification, or change the relative importance of allied capacity. In that sense the decision model is recursively endogenous to policy and geopolitical change: a material external shock is a trigger to update the evidence cut-off, recode affected x_{ij} entries, and rerun DEMATEL

and TOPSIS rather than to treat the 1 August 2026 matrix as a permanent causal map.

5.5 Implications for technology policy and decision analysis

For technology policy, the findings shift attention from lists of "critical" items toward the institutional conditions of usable alternatives. Material lists remain necessary for monitoring, but they are not sufficient for prioritization. A government should ask five questions for each alleged chokepoint. At which layer does concentration occur? Is the input functionally specific? How long does qualification take? Which policy changes actual switching capacity? Does the intervention remain useful if the architecture changes? These questions are especially important for 6G because the technology is still being defined. Recent work surveys integrated sensing and edge AI as a candidate 6G research direction and identifies technical and deployment questions that remain open [80]. It does not test supplier-qualification policies; the recommendation to keep qualification rules revisable follows from this study's scenario analysis rather than from that survey.

The findings also suggest a practical governance structure. A cross-agency resilience board should not merely aggregate project proposals. It should maintain the criteria codebook, publish evidence standards, oversee shared laboratories or recognition arrangements, and commission periodic scenario analyses. Procurement agencies and major operators can provide demand signals without dictating one technical architecture. Standards bodies and research programs can identify where interoperability and substitution are technically plausible. Environmental agencies should be included early, because environmental compatibility influences speed, cost, and durability rather than entering only after a project is selected.

For decision analysis, the study demonstrates a specific value and a clear boundary of evidence-calibrated MCDM. DEMATEL makes directed criterion interdependence visible; TOPSIS prevents a strong score on one dimension from automatically defining the best overall profile. The combination is useful when the desired output includes both causal leverage and compensatory ranking. It nevertheless does not eliminate normative choice: structural prominence is not synonymous with social preference, which is why equal and policy-specific weights are reported separately. Decision-makers should disclose their weight profile and treat sensitivity as part of the substantive result rather than as a technical appendix.

More uncertainty-aware MCDM families are plausible alternatives for a pre-commercial 6G problem. Fuzzy, intuitionistic-fuzzy, interval-valued, rough-set, grey-system, and probabilistic methods can represent imprecision when membership functions, intervals, linguistic distributions, or probability structures are independently elicited or empirically justified; recent supply-chain studies illustrate fuzzy and grey DEMATEL variants [42-43, 45]. The present study retains crisp DEMATEL–TOPSIS because its evidence protocol yields auditable ordinal anchors, whereas assigning fuzzy membership functions or probability distributions without an additional elicitation layer would introduce new unobserved assumptions rather than remove uncertainty. This is a design choice, not a claim of methodological superiority. No comparative fuzzy/grey reranking is reported here, so method-choice robustness remains untested and the paper's novelty is deliberately framed as the evidence architecture and 6G policy application rather than as an algorithmic advance.

The document-coded design is therefore best treated as a transparent interim benchmark when a technology is pre-commercial and expert access is limited. It is not a substitute for stakeholder elicitation. A stronger next validation step would independently recode X and A with trained coders, report agreement and adjudication, then compare the evidence-coded baseline with a Delphi or multi-stakeholder panel spanning telecommunications engineering, semiconductor materials, supply-chain management, public procurement, environmental assessment, and security policy. A subsequent method comparison could place the same validated judgments into a fuzzy, grey, interval, or probabilistic MCDM framework. Agreement across those exercises would provide external and method-choice validation that the present single-coder sensitivity analysis cannot supply.

6. Limitations

Several limitations qualify the findings. First, the model addresses the emerging 6G material and component ecosystem rather than an observed commercial 6G supply chain. ITU-R M.2160 establishes an IMT-2030 framework rather than a universal hardware specification [1]; this study does not claim that mature commercial 6G procurement patterns have already been observed. The analysis therefore evaluates adaptive policy capabilities, not a fixed technology forecast. A different architecture could change the relevance of particular materials and the performance of capacity or stockpile policies. The relevance of any specific radio-frequency material is contingent on standards evolution, qualified alternatives and feasible manufacturing pathways.

Second, the direct-influence and performance matrices were coded by one analyst from verified public evidence. No second coder, formal inter-coder agreement statistic, or stakeholder validation exercise was available. The anchored replication rubric and coding memoranda improve transparency but do not transform single-coder judgments into consensus. The results should therefore be interpreted as an auditable baseline. Independent recoding with Cohen's kappa or an appropriate multi-rater statistic, followed by adjudication and stakeholder validation, is required before claiming measurement reliability across coders.

Third, the model uses ordinal scores rather than project-level cost and time estimates. This is appropriate for a cross-policy comparison under pre-commercial uncertainty but cannot replace engineering feasibility studies, lifecycle assessment, fiscal appraisal, or a direct estimate of the economic cost of a realized 6G disruption. No such observed commercial 6G disruption cost series exists in the evidence base. The cost criterion therefore uses mechanism-level evidence from production networks and semiconductor shortages rather than fabricated 6G monetary values. A specific refinery, recycling facility, laboratory network, or stockpile program would require local data on scale, energy, permitting, demand, qualification time, and opportunity cost.

A further methodological limitation is that the reported robustness exercises vary weights but retain vector normalization, the crisp 1–9 performance matrix, and the DEMATEL–TOPSIS architecture. The study does not test min–max normalization or rerank the alternatives with fuzzy, grey, interval-valued, rough-set, or probabilistic MCDM. The stability of A6 should therefore be described as conditional on the reported model class. Comparative method analysis is a priority once independently validated score intervals or membership functions are available.

Fourth, the base scenario is jurisdiction-neutral but not universal. Resource-producing states, large markets, and connector economies face different constraints. The scenario analysis illustrates how preferences alter the ranking, but it does not model every institutional setting. The supplementary workbook is designed so that users can change both weights and performance scores for a defined jurisdiction.

Finally, resilience policies and geopolitical events can change the system they evaluate. Subsidies attract entry, controls induce substitution, standards reshape markets, and external shocks can alter alliance, licensing, or coercion exposure. X should therefore be treated as a time-stamped causal representation. A material change in export controls, conflict, technology architecture, supplier qualification, or processing concentration should trigger recoding of affected relations and a new model run. The proper use of the present results is to discipline a decision at the 1 August 2026 evidence cut-off, not to claim permanent optimality.

7. Conclusion

6G supply-chain resilience is a decision problem under technological and geopolitical uncertainty. A fixed mineral list cannot capture the layered dependencies that run from mining and high-purity processing to components, equipment, qualification, standards, and repair. The evidence-calibrated DEMATEL analysis identified visibility, innovation compatibility, environmental compatibility, geopolitical-risk reduction, and administrative feasibility as net causal capabilities. Durability, capacity, and scalability were the most systemically prominent criteria.

The TOPSIS analysis ranked shared supplier qualification and certification platforms first, with the largest baseline separation from the next alternative. A6 remained first under equal weighting, four preference scenarios, criterion deletion, and 10,000 stochastic weight perturbations. This establishes stability under the reported weight changes within the fixed coded matrix, not external stakeholder validation or invariance to alternative MCDM formalisms. Joint research and standards alliances ranked second. Recycling and substitution and multi-sourcing formed a preference-sensitive middle cluster. Domestic or allied capacity remained important but was penalized for speed, cost, and implementation constraints; stockpiles and controls were valuable primarily under defined scenarios.

The resulting policy recommendation is sequential. Build visibility and common qualification infrastructure first. Use diversification, research alliances, and substitution to expand the feasible supplier and technology set. Invest in physical capacity where evidence identifies durable chokepoints, and use stockpiles or controls narrowly when the disruption scenario warrants them. This sequence does not eliminate interdependence. It makes interdependence more observable, substitutable, and governable while preserving the technological openness required for an emerging 6G ecosystem.

Declaration of generative AI use

During preparation of revisions to this manuscript, the author used OpenAI ChatGPT to assist with language and readability, evaluating the alignment between cited literature and the scope of textual claims, literature-search support, mathematical notation and document formatting, and preparation of the revision response and supporting documents. In the October 2026 final-revision work, AI assistance included a limited cross-check of values already supplied in Supplementary Workbook S1 and preparation of separate figure files; this stage did not fabricate or alter analyst-coded DEMATEL or TOPSIS matrices, invent expert or stakeholder inputs, or produce unreported empirical findings. The author remains responsible for confirming the provenance of the original research inputs and any AI involvement in earlier revisions. AI-generated suggestions are subject to the author's critical review and source-level verification before submission. Scientific judgments, analyses, interpretations, conclusions, and responsibility for the final manuscript remain with the author.

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Data availability

The study identifies Supplementary Workbook S1 as the essential replication file for the reported calculations, including S1_X_Direct, S2_T_TotalRelation, S3_DEMATEL_Memos, S4_A_Performance, S5_TOPSIS_Calculation, S6_ScenarioWeights, and S7_Robustness. The workbook must accompany the final submission to enable computational verification of the original analysis. Supplementary materials associated with this article are available online and can be accessed via the journal website: https://ojs.luminescience.cn/DMA/article/view/676.

Ethics statement

The study used publicly available documents, published research, and non-personal aggregate information. It did not involve human participants or personal data; ethics approval was not required.

Conflicts of interest

The author declares no conflict of interest.

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