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How Does Industrial Relocation Reshape Industrial Chain Resilience? A Theoretical Analysis Based on Complex Production Networks

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Abstract

Industrial relocation reshapes both the geography of production and the input relationships linking firms, with implications for delivery under regional disruptions. We develop a directed production-network model in which critical suppliers may exit as orders are redirected. Resilience is assessed by expected maximum deliverable output and the probability of failing to meet a minimum delivery target across disruption states. The two-region model shows that geographic dispersion alone need not improve either measure. Following the exit of an incumbent supplier, both measures improve only if the destination can meet the target independently and the expected location gain exceeds the loss of inputs at the origin. A privately profitable relocation decision may nevertheless reduce deliveries across the production network. Even if the final configuration is more resilient, firms remaining at the origin may be unable to finance supplier retention until an independent production path is operational at the destination, creating a temporary supply gap. A three-stage numerical example further shows that moving the same share of assembly capacity can produce opposite resilience outcomes under different upstream production arrangements. The results point to the importance of independent delivery capacity, the continued operation of critical suppliers, and coordination between relocation and changes in production relationships.

Keywords

Industrial Relocation; Industrial Chain Resilience; Production Networks; Interregional Production Specialization; Regional Disruptions

1. Introduction

Relocating a production stage to a region less exposed to disruption may help an individual firm maintain output, without necessarily strengthening delivery across the entire industrial chain. When the firm redirects orders, its former supplier may

lose enough business to become unviable, depriving other customers in the origin of inputs even though their facilities remain in place. Moving assembly capacity creates a related difficulty. Unless the destination also has access to the necessary raw materials and intermediate processing, relocated assembly may still depend on upstream facilities in the origin. Production is then geographically dispersed, but the bottleneck remains shared. Evidence from firms in Pakistan that adjusted production locations, sourcing, and transport routes following floods [1] illustrates why changes in location and production relationships must be examined together.

The relevant question is therefore not whether production is spread across more locations, but when the resulting network can maintain deliveries during disruption. The location of vertically linked industries depends on trade costs and the geography of production stages [2, 3], while research on symbiotic systems evaluates host locations in terms of stability, coordination, and sustainability [4]. Studies of supply-chain resilience emphasize network relationships and the roles of multiple stakeholders [5]; evidence from passive industrial relocation also documents the vulnerability of suppliers connected to relocating firms [6]. A broader production-network literature links input dependencies to aggregate fluctuations [7, 8] and shows how input-specific shocks and natural disasters propagate between firms [9, 10]. Models with endogenous links explain why firms establish or terminate supplier relationships in response to incentives and uncertainty [11, 12]. For a given final product, the maximum-flow/minimum-cut theorem [13] provides a way to identify binding delivery constraints. Work on multisourcing, resilience, and the fixed costs of production links [14–16, 18] likewise suggests that an alternative route offers protection only if it can operate without the same indispensable upstream facility.

These studies clarify production location, network fragility, and sourcing adjustment, but leave two closely related questions unresolved in the setting considered here. First, when relocation simultaneously changes the location of production and the survival of key suppliers, what conditions ensure an improvement in both expected deliveries and the probability of meeting a minimum supply target? Second, can a final configuration improve these measures even though the transition exposes remaining firms to supply losses? We examine these questions in a directed production network, derive the relevant location, independent-delivery, and financing thresholds in a two-region model, and compare alternative upstream structures while holding the relocated assembly share fixed. This approach distinguishes a wider geographic footprint from an effective alternative production path and identifies the conditions under which the benefits of relocation can be sustained during the transition.

2. Model Setup: Regional Production Networks and Resilience

2.1. Production Nodes, Supply Links, and Disruptions

We model production of a single final good as a directed network. Nodes represent plants, processing facilities, or delivery facilities; ℓ_i and r_i denote the production stage and region of node i, respectively. Directed edges represent qualified input transactions or transport routes, each with a capacity measured over the observation period. We express these capacities in final-output-equivalent units and allow qualified facilities at the same stage to substitute for one another along usable routes. To avoid counting a plant's capacity more than once, each plant is split into input and output nodes connected by a capacity-constrained edge. Let x denote a relocation plan and 0 the no-relocation benchmark. The associated production network, $\mathcal{N}_x = (V_x, E_x)$, contains the nodes and links available under that plan. Relocation may shift a production stage between regions, redirect transactions between stages, or both. Capacity in another region provides a genuine alternative only if it forms part of a complete, qualified path to final delivery. Otherwise, a shared upstream facility may remain the binding bottleneck.

The maximum-flow representation requires a specific production technology. We consider one final good and use fixed input coefficients to convert each stage's capacity into equivalent units of final output. Inputs of the same type may be substituted along qualified routes; complementarities between distinct indispensable inputs are not modeled. Maximum flow therefore measures the delivery capacity implied by these technological and routing assumptions, rather than general-equilibrium welfare or aggregate output across products. Let ω index a joint disruption state in a finite state space, with probability π_ω. All relocation plans are evaluated under the same underlying shock distribution, although the repositioning of facilities and links changes their exposure. Available capacity on edge e is

$$c_e^x(\omega) = u_e^x \, \chi_e^x(\omega), \qquad 0 \le \chi_e^x(\omega) \le 1. \tag{1}$$

In Equation (1), u_e^x denotes installed or contracted capacity and $\chi_e^x(\omega)$ the proportion available after accounting for disruptions to the relevant production, transport, and supporting facilities. Links that depend on a common supplier, logistics hub, or utility may fail together. Each such facility is represented by a capacity-constrained node to prevent its output from being counted repeatedly. Unqualified routes and links to suppliers that have exited are assigned zero capacity. The shock state space covers both regional disruptions and failures of individual facilities.

2.2. Procurement Reallocation and Supplier Exit

Relocation may alter procurement contracts and order volumes before any disruption occurs, thereby affecting whether established suppliers remain in business. Let $D_i(x)$ denote expected contracted deliveries by supplier i under relocation plan x, accounting for the contract's operating conditions. The supplier earns a contribution margin $w_i > 0$ per unit and incurs an avoidable fixed

operating cost $F_i > 0$ over the observation period. If it receives an enforceable retention payment $T_i(x)$, it remains active when

$$w_i D_i(x) + T_i(x) \geq F_i. \tag{2}$$

We assume that suppliers continue operating at break-even. Deliveries, margins, and fixed costs are measured over the same period, and any nonnegative retention payment must be agreed and enforceable before disruption occurs. Supplier participation is determined before the shock; delivery is then allocated across qualified paths that remain available. Maximum flow captures feasible delivery under the resulting capacities and contractual links, not a market-clearing quantity chosen by decentralized firms. The loss of orders from a relocating customer may therefore cause a supplier to exit and disrupt other customers still operating in the origin.

2.3. Deliverable Output and Resilience Measures

We connect input sources to a common source node and final delivery points to a common sink. A terminal edge limits deliveries to one unit, an amount every plan can deliver without disruption. Let $\mathcal{F}_x(\omega)$ denote the set of feasible flows satisfying the network's conservation and capacity constraints, $\mathrm{val}(f)$ the flow reaching the sink, and $\mathcal{K}_x$ the set of directed source–sink cuts. The maximum-flow/minimum-cut theorem gives deliverable output as

$$Y_x(\omega) = \max_{f \in \mathcal{F}_x(\omega)} \mathrm{val}(f) = \min_{K \in \mathcal{K}_x} \sum_{e \in K} c_e^x(\omega). \tag{3}$$

The capacity of a cut is the sum of the capacities of edges directed from its source side to its sink side. Because raw-material production, intermediate processing, and final delivery may each constrain throughput, a minimum delivery target y_c is met in a particular state if and only if every source–sink cut has capacity of at least y_c. Feasible flows satisfy edge-capacity limits and conservation at intermediate nodes. Plant-splitting edges impose production constraints, and the terminal edge caps final delivery, ensuring that shared facilities are not counted more than once. For a fixed target $0 < y_c \leq 1$, we measure resilience using expected deliverable output R_x and shortfall probability S_x.

$$R_x = \sum_\omega \pi_\omega Y_x(\omega), \qquad S_x = \Pr\{Y_x(\omega) < y_c\}. \tag{4}$$

We regard the supply-maintenance dimension of resilience as improved when expected deliverable output does not fall, shortfall probability does not rise, and at least one of the two comparisons is strict. Conversely, resilience deteriorates when expected output does not rise, shortfall probability does not fall, and at least one measure worsens. If both are unchanged, the outcome is neutral; if they move in opposite directions, the trade-off is reported rather than collapsed into a single ranking. Comparisons hold constant the final product, observation period, delivery target, and joint distribution of shocks. These measures describe the ability to maintain deliveries during disruption; they do not capture recovery speed or longer-run adaptation.

3. Network Reconfiguration and Relocation Thresholds

3.1. General Network Effects and Delivery Bottlenecks

For each disruption state, define the difference in deliverable output between a relocation plan and the benchmark as $\Delta Y_x = Y_x - Y_0$, with $a^+ = \max\{a, 0\}$ denoting the positive-part operator. Expected gains and losses are summarized by G_x and L_x. Let P_x^+ be the probability mass shifting from a shortfall to meeting the target and P_x^- the mass shifting in the opposite direction. The changes in expected output and shortfall probability are then

$$R_x - R_0 = \mathbb{E}[(\Delta Y_x)^+] - \mathbb{E}[(-\Delta Y_x)^+] = G_x - L_x \tag{5}$$

$$S_0 - S_x = \Pr(Y_0 < y_c \le Y_x) - \Pr(Y_x < y_c \le Y_0) = P_x^+ - P_x^- \tag{6}$$

Proposition 1. Relocation improves the supply-maintenance dimension of resilience if and only if $G_x \ge L_x$ and $P_x^+ \ge P_x^-$, with at least one inequality strict. It worsens that dimension when both inequalities are reversed and at least one is strict. Equality in both comparisons implies no change, while opposing movements must be assessed separately. Equation (5) nets output gains against losses across disruption states; Equation (6) instead records probability mass crossing the minimum delivery threshold. A state-specific output gain affects shortfall probability only when the delivery target is crossed.

Proposition 1 provides the criterion for comparing relocation outcomes in the two-region model. Alternative configurations can be represented within a common network by assigning zero capacity to inactive links. If all other capacities remain unchanged, adding a qualified route or expanding an existing edge cannot reduce maximum flow. It raises flow strictly, however, only when every originally binding minimum cut gains capacity. When relocation also removes capacity or ends supplier relationships, the binding cut must be identified afresh in the resulting network. The value of a new link cannot be inferred without accounting for the links that have disappeared.

Consider an interval over which effective network topology remains fixed, relocation intensity x changes continuously, and each edge capacity has a right derivative. Let $\mathcal{K}_x^*(\omega)$ be the set of binding minimum cuts. In any disruption state, the right-hand marginal change in deliverable output equals the smallest capacity change among these cuts:

$$D_+ Y_x(\omega) = \min_{K \in \mathcal{K}_x^*(\omega)} \sum_{e \in K} D_+ c_e^x(\omega) \tag{7}$$

A finite network has finitely many cuts. Those with capacity strictly above the minimum remain nonbinding for sufficiently small changes, so the right derivative of maximum flow depends on the cuts that bind initially. With a unique binding cut, its capacity derivatives determine the result. Averaging these state-specific effects by their probabilities gives the local marginal change in expected output. Shortfall probability need not respond smoothly: a continuous change in output may produce a discrete jump when delivery reaches the specified target.

This calculation applies only while network topology is unchanged and capacities

vary smoothly. Supplier exit can terminate several links simultaneously, so the appropriate comparison is between the full networks immediately before and after exit, rather than an extrapolation of a local derivative. At a fixed relocation share, removing a supplier without adding alternative capacity cannot increase maximum flow. Delivery falls strictly in a state when a cut in the post-exit network has capacity below the pre-exit maximum. Any replacement facility or contract already operational at the time of exit must be included in that comparison.

3.2. Supplier Exit and Relocation Thresholds in Two Regions

Suppose final-stage production is initially located entirely in region A and a share $\theta \in [0,1]$ is transferred to region B. Binary variables $A, B \in \{0,1\}$ indicate whether the respective regions operate. Their probabilities are $p_A = \Pr(A = 1)$, $p_B = \Pr(B = 1)$, and $q = \Pr(A = 1, B = 1)$, with $0 < q < p_A < p_B < 1$ and $q \geq p_A + p_B - 1$. Assembly in B purchases inputs locally, while its supplier can also serve plants that remain in A. If the incumbent supplier in A survives, those plants continue to source locally; after it exits, they depend on inputs from B and can operate only when both regions are available. Without relocation, $Y_0 = A$, $R_0 = p_A$, and $S_0 = 1 - p_A$. We use subscripts E and K for the exit and retention cases. Supplier exit thus makes production remaining in A dependent on B, whereas retention preserves a qualified local production path in each region.

Equation (8) rests on three assumptions: total final-stage capacity is normalized to one; the supplier in B can provide inputs for all assembly capacity when both regions operate; and qualified interregional transport is available without a separate independent transport shock. Once the supplier in A exits, its remaining assembly capacity can operate only when A is available and inputs can be delivered from B. These assumptions isolate the mechanism and do not imply that every destination already possesses the required supporting capacity.

$$Y_E = (1 - \theta)AB + \theta B, \qquad Y_K = (1 - \theta)A + \theta B. \tag{8}$$

After the supplier in A exits, increasing θ shifts more output to B, where production can continue even when A is disrupted. Relative to the benchmark, the expected gain from relocating capacity is $\theta(p_B - p_A)$; the loss from eliminating the original input source is $(1 - \theta)(p_A - q)$. The net effect on expected output is

$$R_E - R_0 = \theta(p_B - p_A) - (1 - \theta)(p_A - q) = (p_B - q)(\theta - \theta_R). \tag{9}$$

The threshold $\theta_R = (p_A - q)/(p_B - q)$ is the smallest relocation share that restores benchmark expected output. When only B operates, deliverable output equals θ; when only A operates, output is zero because the necessary inputs from B are unavailable. The resulting change in shortfall probability is

$$S_E - S_0 = \begin{cases} p_A - q, & \theta < y_c, \\ -(p_B - p_A), & \theta \geq y_c. \end{cases} \tag{10}$$

Proposition 2. Conditional on exit of the incumbent supplier in A, expected output increases strictly and shortfall probability decreases strictly if and only if $\theta \geq y_c$ and $\theta > \theta_R$. Both measures strictly deteriorate if and only if $\theta < y_c$ and $\theta < \theta_R$. At

$\theta = \theta_R$, expected output is unchanged; shortfall probability falls when $\theta \geq y_c$ and rises otherwise. For $\theta_R < \theta < y_c$ or $y_c \leq \theta < \theta_R$, the measures move in opposite directions. Table 1 summarizes these cases.

Table 1. Resilience outcomes after the supplier at the origin exits

Destination B can independently meet target	$\theta < \theta_R$	$\theta = \theta_R$	$\theta > \theta_R$
$\theta < y_c$	R↓ / S↑	R= / S↑	R↑ / S↑
$\theta \geq y_c$	R↓ / S↓	R= / S↓	R↑ / S↓

Note: R denotes expected deliverable output, and S denotes shortfall probability. Arrows indicate changes relative to no relocation; = indicates no change. Rows distinguish whether B meets the minimum target and columns compare the relocation share with the output-recovery threshold.

On the exit branch, expected output rises linearly with the relocated share at rate $p_B - q$, whereas shortfall probability changes only at the independent-delivery threshold. It decreases by $p_B - q$ when B first acquires enough capacity to meet the target without A. Holding regional operating probabilities constant, a higher probability of joint operation q lowers the expected-output threshold θ_R: plants remaining in A can then obtain inputs from B in more states. Once B meets the target independently, shortfall probability equals the probability that B is disrupted, $1 - p_B$.

3.3. Supplier Retention and Financing Constraints

With the original supplier retained in A, both regions have qualified local input paths and the gain in expected output relative to the benchmark is $\theta(p_B - p_A)$. Define I_A as the indicator that capacity remaining in A meets $1 - \theta \geq y_c$; define I_B analogously for relocated capacity in B meeting $\theta \geq y_c$. The difference between supplier retention and exit at the same relocation share is

$$S_E = 1 - q - (p_B - q)I_B, \qquad S_E - S_K = (p_A - q)I_A. \tag{11}$$

Proposition 3. Holding the relocation share fixed, retaining the supplier in A increases expected output relative to exit by $(1 - \theta)(p_A - q)$. When capacity remaining in A independently meets the delivery target, retention also lowers shortfall probability by $p_A - q$, whether or not B meets that target. The additional protection arises when A operates and B does not. If $y_c \leq \theta \leq 1 - y_c$, both regions can independently deliver the required quantity, and shortfall probability becomes $1 - p_A - p_B + q$, which is $p_B - q$ below the benchmark. If only A meets the target, retention returns shortfall probability to its benchmark level. If only B does, shortfall probability is $1 - p_B$; if neither does, it is $1 - q$, even when the supplier in A remains active.

Preserving the incumbent supplier may require a payment. Let w be its unit contribution margin and F its fixed operating cost, with $0 < F < wp_A$. Without compensation, remaining orders support continued operation only up to $\theta_c = 1 -$

$F/(wp_A)$. Exit at this boundary reduces expected output by $(1-\theta_c)(p_A-q)$. At any relocation share, the minimum payment needed for retention is $T_{\min}=\max\{0,F-wp_A(1-\theta)\}$. If firms remaining in A earn a unit contribution margin v, their aggregate willingness to pay is bounded above by $T_{\max}=v(1-\theta)(p_A-q)$. Assuming enforceable transfers and no additional coordination cost, retention can be financed when $T_{\min}\le T_{\max}$, equivalently

$$\theta \le \theta_F = 1-\frac{F}{wp_A+v(p_A-q)}. \tag{12}$$

To preserve independently viable local delivery paths in both regions through supplier retention, the relocated share must satisfy $y_c \le \theta \le \min\{1-y_c,\theta_F\}$. The feasible interval is nonempty if and only if $y_c \le 1/2$ and $F \le (1-y_c)[wp_A+v(p_A-q)]$. Any bargaining or coordination expense must also fit within the difference between the maximum willingness to pay and the minimum retention payment. These conditions establish whether the original supplier can be retained at a specified allocation of capacity; they do not imply that a private firm will choose that allocation once relocation costs are included. With regional operating probabilities fixed, increasing their joint operating probability q also increases the probability of a simultaneous shutdown. When each region can meet the delivery target independently, S_K therefore increases with q. A higher q also diminishes the value of retaining the original supplier as a backup, reducing willingness to pay and the financing threshold θ_F. Regional shock dependence thus matters for both delivery reliability and the feasibility of supplier retention; differing recovery times, not modeled here, could affect longer-horizon assessments.

3.4. Phased Relocation and Transition Feasibility

Consider a terminal relocation share θ_e at which the incumbent supplier in A has exited and both resilience measures strictly improve relative to the benchmark. Relocation proceeds continuously from zero to θ_e, so every intermediate share is reached. Firms remaining in A may renegotiate enforceable retention payments at each stage, without coordination costs. Define $\theta_*=\max\{y_c,\theta_R\}$ as the smallest share at which supplier exit is no worse than the benchmark on either measure. We require $R \ge R_0$ and $S \le S_0$ throughout the transition.

Proposition 4. Under the stated terminal and financing assumptions, a continuous relocation path can avoid any deterioration relative to the benchmark at every intermediate stage if and only if

$$y_c \le 1/2, \qquad \theta_F \ge \theta_* = \max\{y_c,\theta_R\}. \tag{13}$$

If $y_c > 1/2$, there is an intermediate interval $1-y_c<\theta<y_c$ in which neither region can meet the target independently. Under either supplier arrangement, shortfall probability is then $1-q>S_0$, above the benchmark. Alternatively, if $\theta_F<\theta_*$, the interval $\theta_F<\theta<\theta_*$ contains relocation shares for which firms remaining in A cannot finance supplier retention, while exit worsens at least one resilience measure. Either failure therefore rules out a uniformly feasible transition. When

Equation (13) holds, by contrast, the incumbent supplier can be retained until θ_*, maintaining expected output at or above the benchmark while at least one region independently meets the delivery target. The supplier may then exit when $\theta > \theta_c$ without worsening either measure. So long as its original orders cover operating costs, retention requires no additional payment.

Proposition 4 establishes the existence of a feasible sequence of capacity reallocations and supplier-retention agreements for a specified terminal configuration. It does not describe a dynamic equilibrium with construction delays, inventories, or intertemporal financing. The key distinction is between the relocation share required for the final network to maintain deliveries and the share up to which firms in A can afford to retain the original supplier. Where these thresholds overlap, the supplier can remain operational until an independent route is ready in B. The natural-exit threshold and the financing limit are separate constraints; by assumption, the supplier continues operating at the break-even boundary.

4. Numerical Illustrations

4.1. Alternative Upstream Production Networks

The numerical illustration uses three production stages: raw materials U, intermediate processing M, and final assembly D. Regional operating probabilities are $p_A = 0.75$ and $p_B = 0.90$, with joint probability $q = 0.675$; the minimum delivery target is $y_c = 0.50$. All stages are initially located in A. Each alternative reallocates half of assembly capacity to B, and every configuration can deliver one unit when both regions operate. We keep the relocation share and disruption probabilities fixed, varying only the locations of upstream stages and the qualified links between them. Figure 1 depicts the four production networks, while Table 2 gives their deliverable output in each regional disruption state.

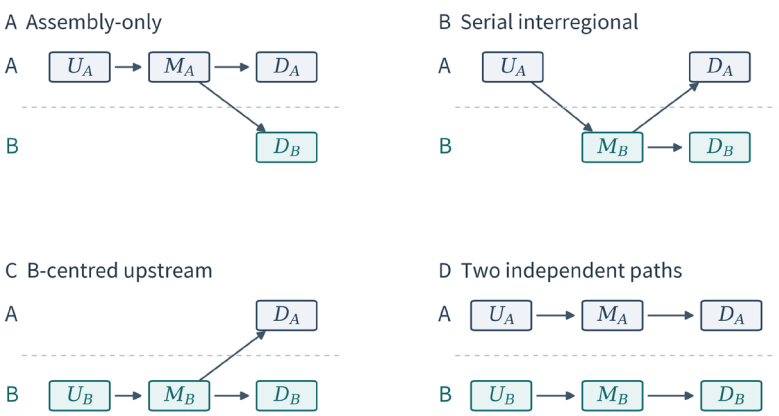


Figure 1. Four production networks with the same relocated assembly share

Notes: U, M, and D denote raw-material production, intermediate processing, and final assembly, respectively; subscripts indicate regions. Assembly capacity is 0.50 at each assembly node. Upstream capacity is 1 in configurations A–C, while each local path in configuration D has capacity 0.50.

Table 2. Deliverable output under alternative regional disruption states

Production network	Y_{00}	Y_{10}	Y_{01}	Y_{11}	R	S
No relocation	0	1	0	1	0.7500	0.2500
A. Assembly only	0	0.50	0	1	0.7125	0.2500
B. Serial cross-regional	0	0	0	1	0.6750	0.3250
C. B-centered supply	0	0	0.50	1	0.7875	0.1000
D. Complete local paths	0	0.50	0.50	1	0.8250	0.0250

Note: Subscripts of Y denote operating states of A and B, respectively (1 = operating; 0 = disrupted). All networks use identical state probabilities and a minimum delivery requirement of 0.50. R is expected deliverable output; S is shortfall probability.

In configuration A, only assembly is relocated. Raw-material production and intermediate processing remain in A, allowing assembly there to deliver 0.50 units when A operates alone, exactly meeting the target. Assembly in B, however, still requires inputs from A. Expected output is therefore 0.7125, with shortfall probability of 0.2500. When all processing moves to B but raw materials remain in A, assembly in either region requires both regions to operate. Expected output falls to 0.6750 and shortfall probability rises to 0.3250. In this arrangement, serial interregional specialization creates a shared bottleneck rather than an alternative delivery path.

Configuration C gives B its own raw-material and processing capacity, while assembly remaining in A sources intermediate inputs from B. B can now deliver 0.50 units independently, raising expected output to 0.7875 and reducing shortfall probability to 0.1000. With complete local production paths in both regions, expected output increases further to 0.8250 and shortfall probability falls to 0.0250. The difference lies in the independence of feasible paths, not in the number of assembly sites. When the minimum delivery target increases from 0.50 to 0.60, expected output in the dual-path network remains 0.8250, but shortfall probability rises to 0.3250; the assembly-only and B-centered configurations also have shortfall probability of 0.3250. A meaningful comparison therefore requires a common target. Table 2 assumes that the capacities and contracts shown in each configuration are operational. Section 4.2 examines the additional financing constraints on retaining the original supplier.

4.2. Relocation Thresholds, Financing, and Private Incentives

With the baseline disruption probabilities, restoring benchmark expected output

after supplier exit requires a relocation share of $\theta_R = 1/3$. At $\theta = 0.20$, expected output is 0.7200 and shortfall probability 0.3250, both worse than their benchmark values of 0.7500 and 0.2500. Increasing the share to $\theta = 0.40$ raises expected output to 0.7650, but shortfall probability remains 0.3250 because B still cannot meet the target independently. Figure 2 places this independent-delivery threshold alongside the expected-output recovery threshold and the financing limit for supplier retention.

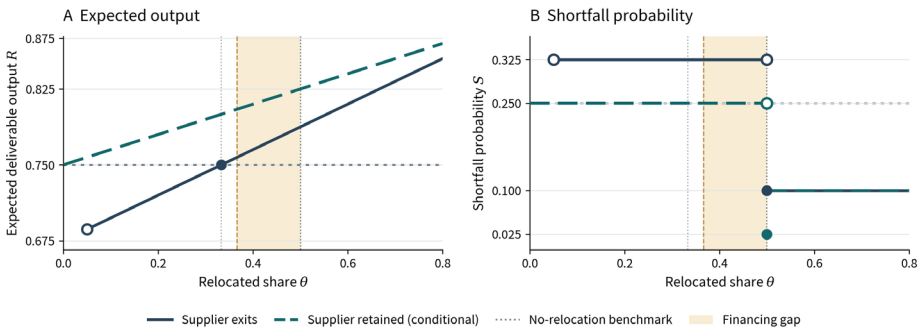


Figure 2. Relocation thresholds and the gap in transition-stage financing

Note: Without a retention payment, the supplier exits for θ>0.05. The dashed retention branch assumes continued operation. Shading marks $\theta \in (11/30, 0.50)$, where financing is infeasible and exit fails the joint criterion. Open markers exclude endpoints; filled markers include them. At θ=0.50, retention yields S=0.025.

For $w = 0.20$, $v = 1$, and $F = 0.1425$, the supplier's natural-exit threshold is $\theta_c = 0.05$, while the maximum relocation share consistent with financing retention is $\theta_F = 11/30$, below the joint resilience threshold $\theta_* = 0.50$. Supplier exit at $\theta = 0.50$ improves both measures, but a continuous relocation must pass through $\theta = 0.40$. At that share, keeping the supplier active requires a payment of 0.0525, against a maximum willingness to pay of 0.0450 by firms remaining in A, leaving a financing gap of 0.0075. Because B cannot yet deliver the target independently, exit raises shortfall probability to 0.3250. Lowering fixed operating cost to 0.10 increases the financing limit to $\theta_F = 5/9$, allowing retention throughout the transition as required by Equation (13). Holding other parameters fixed, feasibility instead requires fixed cost of at most 0.1125 or, with fixed cost at 0.1425, a unit contribution margin of at least 1.8. These thresholds follow from the model and are not empirical estimates for relocation projects.

Private incentives need not align with delivery reliability across the production network. Consider a firm that controls 0.20 units of normalized industry capacity and faces relocation cost $\theta^2/2$, with other parameters unchanged. Without retention payments, its preferred relocation amount is 0.05 while the supplier remains active, yielding profit of 0.15625. If the supplier exits, the firm's preferred

amount is 0.20, yielding profit of 0.1600, compared with 0.1500 without relocation. The firm gains 0.0300 in expected delivery, while other firms lose 0.0600 because input supply in A disappears. Because total industry capacity is normalized to one, the firm's relocation amount also equals the aggregate share moved, within the interval from zero to 0.20. Under retention, its revenues reflect capacity operating in A and in B, net of relocation cost. After supplier exit, the capacity remaining in A produces only when both regions operate, so its operating probability falls from A's marginal probability to the joint probability. The corresponding profit functions are

$$\Pi_K(\theta) = p_A(0.20 - \theta) + p_B\theta - \frac{\theta^2}{2}$$

$$\Pi_E(\theta) = q(0.20 - \theta) + p_B\theta - \frac{\theta^2}{2}$$

With retention, the unconstrained profit-maximizing relocation amount is 0.15, but supplier survival without payment limits it to 0.05, yielding maximum profit of 0.15625 on that branch. With exit, the unconstrained stationary point is 0.225, beyond the firm's capacity of 0.20. Its constrained optimum is therefore 0.20, with profit of 0.1600. Relocation can be privately profitable even as deliverable output declines elsewhere in the network. This calculation is not a characterization of the welfare-optimal allocation.

5. Policy Implications and Conclusions

5.1. Implications for Network-Based Relocation Policy

For critical products, relocation assessments should follow the full sequence from raw materials and intermediate processing to assembly and final delivery. The relevant network includes usable production capacity, interregional transactions, transport routes, and shared supporting facilities. Comparisons should use the same product definition, observation period, and minimum delivery requirement. When particular minimum cuts repeatedly constrain delivery across disruption states, a qualified alternative supplier, additional processing capacity, or a new transport route may relieve the bottleneck. Shared electricity, logistics, and upstream inputs cannot be treated as independent additions to nominal capacity. The order of relocation also matters. Before an essential supplier relationship in the origin is terminated, planners need to establish whether the destination can deliver independently and whether the expected location gain offsets the loss of original inputs. If neither region can meet the target alone during the transition, retaining both suppliers may still leave a shortfall. Temporary backup capacity, final-goods shipments, or additional supporting facilities should then be evaluated as potential means of maintaining delivery.

Firms and public authorities in both regions also need to identify suppliers at risk of exit as orders decline, together with the customers that remain dependent on them. Where financing and contract enforcement are adequate, joint purchasing arrangements or time-limited retention agreements may keep critical links

operational until a qualified alternative path is commissioned. Supplier replacement entails search costs [17], while creating production links can require fixed investment [18]. Evidence on network reorganization following wartime disruption [19] and changes in US sourcing patterns [20] likewise suggests that input relationships may adjust slowly. Withdrawal from an incumbent supplier should therefore be coordinated with the actual availability of replacement production capacity, rather than scheduled solely according to the relocation of assembly plants.

The location of customers also matters for interpreting network-wide results. A regional assessment should identify local delivery points, minimum requirements, and access to interregional inputs. The aggregate measure used here concerns one final good delivered to a common sink; it is not a measure of welfare across all sectors or regions. Configuration C in Table 2 reduces shortfall probability for the product network from 0.2500 to 0.1000. Yet if customers in A require 0.50 units to be delivered through assembly located in A, their shortfall probability may rise from 0.2500 to 0.3250 because that plant now needs both regions to operate. An improvement at the level of the full product network need not therefore improve delivery assurance in every region. A qualified final-goods route from B to A could reduce the divergence, provided that its capacity and reliability under disruption are explicitly included.

5.2. Main Findings and Limitations

Industrial relocation alters delivery bottlenecks by changing both the locations of production stages and the relationships connecting them. In the two-region model, once the incumbent supplier in A exits, expected output can increase and shortfall probability can decline together only if B independently meets the minimum delivery target and the expected location gain exceeds the lost inputs at the origin. On the exit branch, expected output rises with relocated capacity at marginal rate $p_B - q$, while shortfall probability drops discretely when B reaches the target. Retaining the original supplier can further reduce shortfall probability, provided the remaining capacity in A also meets the target independently and retention is financially feasible. More dispersed production is therefore not sufficient: resilience depends on the existence of complete, operational production paths in different regions.

The final configuration and the transition to it must also be distinguished. Even when the destination will eventually support an independent production path, firms remaining in the origin may be unable to finance the incumbent supplier until that path is available. The resulting supply gap can be mitigated through enforceable retention arrangements and appropriate sequencing, but only where the supplier's operating cost and the remaining firms' willingness to pay permit. These conclusions apply to a single final good represented in equivalent-flow units, binary

regional disruptions, and the specified contractual arrangements. They do not incorporate complementarities between indispensable inputs, inventories, gradual capacity commissioning, supplier reentry, or post-shock recovery dynamics. Such features could change the thresholds obtained here.

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