Remote Embodiment and the Globalization of Physical Labor

Teleoperation, Automation, and Labor Arbitrage in a Task-Based Model

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Abstract

Remote teleoperation allows labor located in one country to perform physical tasks in another through robotic capital located at the destination. This paper defines the resulting production mode as remote embodiment and studies its implications for trade, labor demand, and the geography of production. I develop a two-country task-based model in which a physical task can be performed by destination labor, conventional offshore production, or a hybrid technology combining destination robot capital with source-country operator attention. The human input required by the hybrid technology falls with autonomy. The model yields four results. First, lower robot and network costs, a wider international wage gap, and greater autonomy expand the set of physical tasks exposed to cross-border labor competition. Second, autonomy is complementary to remote embodiment at the adoption margin but substitutes for source-country operator labor at the intensive margin; operator employment therefore depends on whether fleet expansion outpaces the decline in human attention per robot-hour. Third, remote embodiment can reshore physical production while leaving the associated control service offshore. Fourth, platform labor-market power determines how much of the cost advantage reaches operators rather than customers or capital owners. The paper derives these results formally, provides transparent numerical illustrations, and proposes an empirical strategy based on task-level teleoperability, firm adoption, network-latency shocks, and operator logs. The analysis implies that robotics may globalize portions of physical labor before it fully automates them.

JEL classifications: F14, F16, J23, J42, O33

1 Introduction

The modern geography of work reflects a basic technological constraint: information can move cheaply across borders, but physical action generally cannot. A software developer in Bengaluru can write code for a firm in San Francisco because both the production process and the deliverable are digital. A worker who picks a box, inserts a component, inspects a machine, or clears a jam has historically needed to be where the object is located.

Remote teleoperation weakens that constraint. A robot, vehicle, or machine remains at a destination worksite. Cameras and robot state are transmitted over a network. A worker in another country supplies perception, judgment, and motor commands. Those commands are converted into machine actions, and the resulting output is produced locally. The labor crosses the border as information even though the task remains physical.

This paper calls that arrangement **remote embodiment**. It is a hybrid production technology:

$$\text{destination robot capital} + \text{source-country labor} + \text{network infrastructure} \longrightarrow \text{local physical output.}$$

Remote embodiment is economically distinct from both conventional offshoring and full automation. In conventional offshoring, production moves toward lower-cost labor and the resulting good or intermediate input crosses a border. Under remote embodiment, the machine and physical output remain at the destination while the control service is imported. Under full automation, the marginal human-control input approaches zero. Remote embodiment occupies the space between the two.

The distinction matters because it expands the set of tasks potentially exposed to international labor competition. Classic offshorability frameworks emphasize whether a service can be delivered electronically over long distances (Blinder 2007). Trade-in-tasks models show how lower coordination costs permit firms to fragment production across borders (Grossman and Rossi-Hansberg 2008). More recent work studies telemigration and the international pricing of remote digital work (Baldwin and Dingel 2021; Brinatti et al. 2022). These frameworks largely treat physical presence as a barrier to service trade. A remotely controlled robot changes that barrier: the service delivered electronically is not the final physical action itself, but the information required to produce it through local capital.

The paper asks four economic questions.

First, **which physical tasks become tradable when remote control is available?** A task must be observable through sensors, controllable through available hardware, sufficiently tolerant of latency, safe to execute remotely, and recoverable without constant on-site labor. These properties act like task-specific trade costs.

Second, **how does autonomy interact with international labor arbitrage?** Autonomy reduces the number of human minutes required per robot-hour. This makes the hybrid technology cheaper and expands adoption. At the same time, it reduces labor required for every deployed robot. The source-country employment effect is therefore not mechanically positive or negative; it is the result of a scale effect and a labor-saving effect.

Third, **what happens to the geography of production?** Remote embodiment makes it possible to keep capital and output in a high-income country while sourcing part of the labor service from a lower-wage country. It can therefore generate a pattern that standard reshoring statistics may miss: domestic physical production rises while imported labor services also rise.

Fourth, **who captures the cost advantage?** The international wage gap creates potential surplus, but it does not determine its incidence. Customers may receive lower prices, destination firms and robot owners may receive higher profits, platforms may take fees, and source-country operators may receive wages tied more closely to their local outside options than to destination productivity. Existing evidence from global remote-work platforms shows that worker location continues to explain substantial wage variation even in a nominally global market (Brinatti et al. 2022).

The paper develops a task-based partial-equilibrium model with two countries. A continuum of destination physical tasks can be produced by local labor or by remote embodiment. The remote technology combines robot cost, local maintenance labor, source-country operator time, and task-specific network or coordination friction. An autonomy parameter reduces operator time per unit of output. Under a monotone teleoperation-difficulty assumption, production is governed by a cutoff: tasks below the cutoff are remotely embodied and tasks above it remain local. The cutoff rises with destination wages and autonomy and falls with source wages, robot costs, and network frictions.

The model produces four propositions. The first characterizes the tradability cutoff. The second decomposes source-country operator employment into labor intensity and the scale of remotely embodied production. The third derives the familiar monopsony markdown for a platform facing an upward-sloping operator labor supply curve. The fourth adds conventional offshore production and shows the conditions under which a task moves from offshore physical production to destination robot production controlled by source-country labor.

This is a theoretical economics paper. The numerical exercises are calibrations used to illustrate mechanisms, not estimates of causal effects or forecasts of market size. A separate empirical section describes the data needed to test the model: task-level teleoperability measures, robot and teleoperation adoption, operator location and compensation, intervention seconds per robot-hour, latency, local employment, and firm output.

The central result can be stated simply:

> Robotics may first make physical labor internationally tradable and only later make it unnecessary.

That sequence differs from the usual automation narrative. It also implies that the global labor-market effects of robotics could begin before robots are capable of operating autonomously for entire shifts.

2 Related literature and contribution

2.1 Trade in tasks and offshorability

The paper is most directly related to the literature on task trade and service offshoring. Grossman and Rossi-Hansberg model offshoring as trade in tasks rather than trade only in final goods. Falling task-trade costs create a productivity effect for the factor whose tasks become easier to offshore, even while individual tasks move abroad (Grossman and Rossi-Hansberg 2008). Remote embodiment adds a new way to trade a task: instead of moving the worksite or shipping a physical intermediate input, the firm transmits control information to labor abroad and embodies that input through capital at the destination.

Blinder's offshorability framework classifies occupations partly by whether the service can be delivered electronically with little loss of quality (Blinder 2007). Physical proximity places many occupations outside that frontier. Remote embodiment does not make every such occupation tradable. It changes the relevant technological question from whether the final service is digital to whether the state information and control commands required for the physical task can be digitized.

Baldwin and Dingel analyze telemigration as cross-border trade in remotely deliverable services and show that reductions in service-trade costs can generate asymmetric effects when lower-wage countries possess latent comparative advantage (Baldwin and Dingel 2021). Brinatti et al. use platform data to show that remote-work wages remain strongly related to worker location and local labor-market conditions (Brinatti et al. 2022). That empirical pattern supports the labor-arbitrage channel modeled here: global access does not immediately eliminate international wage wedges.

2.2 Automation, tasks, and labor demand

The second literature studies automation as a reallocation of tasks from labor to capital. Acemoglu and Restrepo distinguish a displacement effect, in which automation reduces labor's task content, from productivity and reinstatement effects that can raise labor demand elsewhere (Acemoglu and Restrepo 2019). Their empirical work on industrial robots finds negative local employment and wage effects in more exposed U.S. commuting zones (Acemoglu and Restrepo 2020).

Remote embodiment creates a different sequence. Capital does not initially replace labor entirely. Instead, it changes where labor can be supplied and how many units of human attention are needed. The hybrid technology can displace destination labor while creating source-country operator tasks and destination maintenance tasks. As autonomy improves, it subsequently displaces part of the source-country operator input. This paper therefore separates three margins that are often combined:

1. **geographic substitution:** destination labor is replaced by source-country labor;
2. **capital complementarity:** source-country labor becomes productive through destination robot capital;
3. **automation:** software reduces the source-country labor required per unit of robot output.

Bonfiglioli et al. study the interaction between robots and offshoring and show that welfare effects depend on whether automation replaces domestic or foreign tasks (Bonfiglioli et al. 2021). In their setting, robots and foreign labor are alternative ways to perform tasks. The distinctive feature here is that foreign labor and destination robot capital can be complements within the same production mode.

2.3 Platform work and remote robotics

A third literature concerns labor platforms, monopsony, and digitally mediated work. Global platforms can lower search and contracting costs while also concentrating control over matching, reputation, work allocation, and payment. The ILO and World Bank document both the income opportunities and the weak social protection, volatile demand, unpaid search time, and algorithmic management present in online labor markets (International Labour Office 2021; Datta et al. 2023). These issues become more consequential when platform labor is attached to safety-relevant physical systems.

The robotics literature supplies evidence that shared human supervision is technically coherent. Fleet-DAgger formalizes multi-robot, multi-human interactive learning and demonstrates remote supervision in both simulation and physical robot experiments (Hoque et al. 2023). The economic contribution of the present paper is not a claim that arbitrary physical work is already remotely tradable. It is a framework for analyzing the labor-market consequences as the technical cost of remote embodiment falls.

Recent social-science work has begun to describe remote robotics as a digital re-embodiment of labor (Steinhoff, Posada, and Delfanti 2025). This paper complements that qualitative perspective with a formal task-allocation model, comparative statics, and an empirical design.

3 Institutional setting

3.1 The remote-embodiment production stack

A remote-embodiment system generally contains five components.

1. **Local embodiment.** A robot, vehicle, or machine capable of acting on the destination environment.
2. **Observation.** Cameras, joint state, force estimates, and other sensor streams that allow a remote worker or monitoring system to infer the relevant state.
3. **Communication and control.** A relay that transmits state outward and commands inward, often with local low-level stabilization.
4. **Allocation and handoff.** A mechanism that decides when human input is required and routes the task to an available operator.
5. **Local support.** Maintenance, safety supervision, physical resets, loading, and repair that cannot be performed through the network.

The human role can take several forms. At one extreme, an operator continuously drives one robot. In shared autonomy, the robot handles low-level motion while a person supplies goals, waypoints, or difficult substeps. In intervention systems, the policy operates independently until a failure or uncertainty signal triggers human takeover. In the limiting case, a recovery model resolves recurring exceptions automatically and a person handles only novel tail events.

The relevant labor unit therefore changes across stages:

Operating regime	Human role	Labor unit
Continuous teleoperation	Performs the task throughout	Operator-hour per robot-hour
Shared autonomy	Supplies goals or difficult segments	Assisted minutes per robot-hour
Exception intervention	Recovers failures on demand	Intervention-seconds per robot-hour
Autonomous recovery	Handles only novel tail cases	Human seconds per rare event

A concrete human-assisted implementation illustrates the structure. In Northstar's current system, a monitor watches an external task camera and two wrist-camera streams. When an autonomous policy is judged to be failing, the monitor signals a relay to stop policy execution and route the robot to an operator. The operator uses VR controllers; hand poses are transmitted to the relay, inverse kinematics translates them into robot commands, and joint positions and camera streams return to the operator. The system has been operated from India at roughly 150 milliseconds of end-to-end latency. This is an author-supplied engineering example, not an independently audited performance estimate, and it is not used in the model calibration.

3.2 Task characteristics and trade costs

Remote embodiment is feasible only when the total cost of transmitting and embodying labor is below the cost of alternatives. The relevant task characteristics include:

- **observability:** whether sensors reveal the state needed for action;
- **controllability:** whether available hardware can reproduce the required movement and force;
- **latency tolerance:** whether delay and jitter degrade safety or productivity;
- **reset intensity:** how often a person must physically repair or rearrange the environment;
- **safety externality:** the cost of a mistaken or delayed action;
- **social locality:** whether trust, physical presence, or tacit local knowledge is part of the service;

- **standardization:** whether operators can transfer skills across machines and sites.

These characteristics are analogous to iceberg trade costs. A remote operator may supply one hour of effort, but only a fraction arrives as useful physical output after accounting for degraded perception, delay, handoff time, and failed recoveries. Improvements in sensors, control interfaces, broadband, local autonomy, and standardized robot APIs lower this effective trade cost.

3.3 The economic unit: human attention per robot-hour

The main operating variable is not an autonomy label. It is the quantity of human attention used to produce one successful robot-hour.

Let

$$H = \text{human seconds required per successful robot-hour.}$$

A continuously teleoperated robot has approximately $H = 3{,}600$. An intervention system may have a much smaller value if failures are infrequent and rapidly recovered. This quantity combines failure frequency, detection delay, queueing, handoff time, recovery duration, and the probability that a local reset is required.

For economics, H connects engineering progress to labor demand. Lower H reduces variable labor cost, increases the number of robots one operator can support, and expands adoption. It also reduces the amount of source-country labor used per robot. The model below represents this relationship with an autonomy parameter that lowers remote labor hours per unit of output.

4 Model

4.1 Environment

There are two countries: a destination country H and a source country S. The destination has wage w_H and the source has wage w_S, with $w_H > w_S$ in the baseline case. A competitive destination industry produces final output Y using a continuum of physical tasks indexed by $z \in [0, 1]$.

Tasks are aggregated with constant elasticity of substitution $\sigma > 1$:

$$Y = \left[\int_0^1 x(z)^{\frac{\sigma-1}{\sigma}} \, dz \right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

Let $c(z)$ be the minimum unit cost of task z. Cost minimization implies the task price index

$$P = \left[\int_0^1 c(z)^{1-\sigma} \, dz \right]^{\frac{1}{1-\sigma}} \tag{2}$$

and conditional demand

$$x(z) = Y \left(\frac{c(z)}{P} \right)^{-\sigma} \tag{3}$$

The CES structure is not essential for the cutoff result, but it makes the scale effect explicit: a fall in the cost of remotely embodied tasks lowers the price index and raises demand for those tasks.

4.2 Production modes

In the baseline model, each task can be produced in one of two ways.

Destination labor. One unit of task output requires $\ell > 0$ hours of destination labor, giving unit cost

$$c_H = w_H \ell \tag{4}$$

Remote embodiment. The physical task is performed by robot capital at the destination and controlled by labor in the source country. The unit cost is

$$c_E(z, A) = r + w_H m + w_S h(A) + \tau(z) \tag{5}$$

The terms are:

- $r > 0$: robot capital, depreciation, software, and non-labor operating cost per unit;
- $m \geq 0$: destination maintenance, safety, and local-reset labor hours per unit;
- $h(A) > 0$: source-country operator hours per unit;
- $A \geq 0$: autonomy or assistance capability;
- $h'(A) < 0$ and $h''(A) \geq 0$: autonomy reduces human attention at a diminishing rate;
- $\tau(z)$: task-specific remote-control friction, with $\tau'(z) > 0$.

Tasks are ordered so that higher z is more difficult to teleoperate. Difficulty can represent latency sensitivity, poor observability, tactile complexity, or expected reset cost.

The firm chooses remote embodiment when $c_E(z, A) \leq c_H$. Since c_E rises in z, an interior cutoff $z_c \in (0, 1)$ satisfies

$$r + w_H m + w_S h(A) + \tau(z_c) = w_H \ell \tag{6}$$

Thus,

$$z_c = \tau^{-1} \left[w_H(\ell - m) - r - w_S h(A) \right] \tag{7}$$

Tasks $z \leq z_c$ are remotely embodied; tasks $z > z_c$ remain with destination labor.

4.3 Proposition 1: the remote-embodiment cutoff

Proposition 1 (Tradability frontier). Suppose the cutoff is interior, $\tau'(z_c) > 0$, and $\ell > m$. Then:

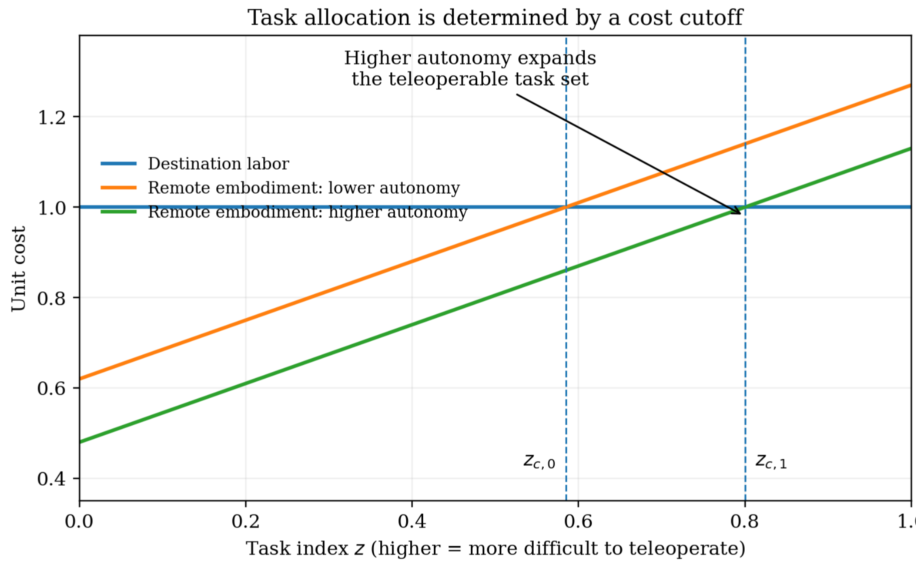

Figure 1: A decline in human-attention cost shifts the remote-embodiment schedule downward and expands the task set assigned to it. The chart is a model illustration, not observed data.

$$\frac{\partial z_c}{\partial A} = -\frac{w_S h'(A)}{\tau'(z_c)} > 0, \qquad \frac{\partial z_c}{\partial w_H} = \frac{\ell - m}{\tau'(z_c)} > 0,$$

$$\frac{\partial z_c}{\partial w_S} = -\frac{h(A)}{\tau'(z_c)} < 0, \qquad \frac{\partial z_c}{\partial r} = -\frac{1}{\tau'(z_c)} < 0 \tag{8}$$

Greater autonomy, a higher destination wage, a lower source wage, and a lower robot cost each expand the range of physical tasks assigned to remote embodiment.

The proposition formalizes labor arbitrage. A wider international wage gap does not automatically make every physical task tradable; it raises the maximum remote-control friction the firm is willing to absorb. Autonomy has the same extensive-margin effect because it lowers the source labor input embedded in each robot-hour.

4.4 Equilibrium task expenditure

Let $\mathcal{E}(A) = [0, z_c(A)]$ denote the remotely embodied set and $\mathcal{H}(A) = (z_c(A), 1]$ the destination-labor set. Total expenditure on task z is $c(z)x(z)$. Because tasks are substitutes, a fall in c_E changes both the allocation of marginal tasks and demand within the remotely embodied set.

The direct cost saving on an embodied task is

$$\Delta(z, A) = w_H\ell - [r + w_H m + w_S h(A) + \tau(z)] \tag{9}$$

The economic gain is not identical to the international wage difference. Robot cost, local support, latency, risk, and platform fees can absorb the wedge. The wage gap matters only after these costs are included.

Figure 2: Comparative statics of the task cutoff under a normalized calibration. Lower source wages and greater autonomy both expand the remotely embodied task set. All values are illustrative.

5 Labor demand and distribution

5.1 Source-country operator employment

Source-country labor used by remote embodiment is

$$L_S^E(A) = \int_0^{z_c(A)} h(A)x(z, A)\, dz \tag{10}$$

Define total remotely embodied task output as

$$Q_E(A) = \int_0^{z_c(A)} x(z, A)\, dz.$$

Then

$$L_S^E(A) = h(A)Q_E(A) \tag{11}$$

and the log derivative is

$$\frac{d \ln L_S^E}{dA} = \frac{d \ln h}{dA} + \frac{d \ln Q_E}{dA} \tag{12}$$

The first term is negative: autonomy reduces operator hours per unit. The second is generally positive because lower costs increase output of existing embodied tasks and move additional tasks into the embodied set.

Proposition 2 (Scale versus displacement). Source-country operator employment rises with autonomy if and only if

$$\frac{d\ln Q_E}{dA} > -\frac{d\ln h}{dA} \tag{13}$$

Autonomy increases source employment when the percentage expansion of remotely embodied output exceeds the percentage decline in operator labor required per unit. Otherwise, source employment falls.

This result separates the short-run and long-run narratives. Early improvements in autonomy can increase operator employment if they make deployments economical across a rapidly expanding fleet. Later improvements can reduce employment if robot-hours grow slowly relative to the fall in human attention. The employment path can therefore be hump-shaped even when the technology improves monotonically.

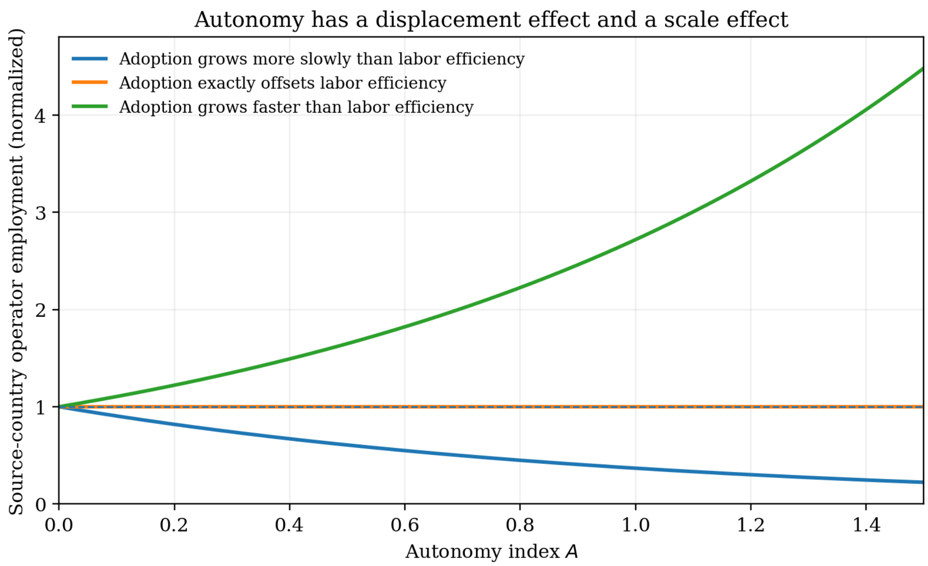

Figure 3: Source-country employment depends on whether fleet and output expansion outpace the decline in human attention per robot-hour. The curves are analytical illustrations.

5.2 Destination employment

Destination labor demand is

$$L_H(A) = \ell \int_{z_c(A)}^{1} x(z,A)\,dz + m \int_{0}^{z_c(A)} x(z,A)\,dz \tag{14}$$

Holding output fixed, moving a marginal task from destination labor to remote embodiment changes local labor by $m - \ell < 0$. This is the direct displacement effect. But lower task costs can raise final output and demand for both remotely embodied and remaining local tasks. Local maintenance, safety, installation, and physical-reset work also expand with the robot fleet.

The net destination employment effect is therefore ambiguous in the aggregate but concentrated in task space. Workers whose tasks are directly below the teleoperation cutoff face geographic substitution. Workers in complementary local tasks can gain. This mirrors the distinction between displacement and productivity effects in task-based automation models (Acemoglu and Restrepo 2019).

The adjustment may be geographically slow. Evidence from earlier trade and robot shocks shows that labor-market losses can remain concentrated in exposed occupations and commuting zones even when aggregate productivity rises (Autor, Dorn, and Hanson 2016; Acemoglu and Restrepo 2020). Remote embodiment may affect a different set of jobs, especially jobs previously considered protected from offshoring because the output was physical.

5.3 Platform labor-market power

Remote embodiment is likely to be organized through platforms or large intermediaries that integrate robots, authenticate operators, route tasks, maintain performance records, and bill customers. These intermediaries can reduce transaction costs, but they may also face upward-sloping labor supply and exercise monopsony power.

Let v denote the marginal revenue product of one unit of operator labor to the platform. Suppose the platform faces source labor supply

$$L(w) = \overline{L}w^{\varepsilon}, \qquad \varepsilon > 0 \tag{15}$$

and chooses wage w to maximize

$$\Pi(w) = (v - w)L(w) \tag{16}$$

The first-order condition gives

$$w = \frac{\varepsilon}{1+\varepsilon}v \tag{17}$$

Proposition 3 (Platform markdown). The operator receives a share $\varepsilon/(1+\varepsilon)$ of marginal revenue product. A less elastic labor supply produces a larger markdown and allows the platform to capture more of the labor-arbitrage surplus.

The result is standard monopsony economics (Manning 2003), but its application here is important. The destination-source wage gap determines potential cost savings; platform competition and source-country outside options determine how those savings are divided. Improvements in robot productivity need not translate proportionately into operator wages.

Platform design also affects unpaid time. If operators are compensated only for active intervention-seconds but must remain available between events, measured wages can overstate compensation per committed hour. A complete empirical wage measure should therefore distinguish active control time, paid standby time, required unpaid availability, training, and task-search time.

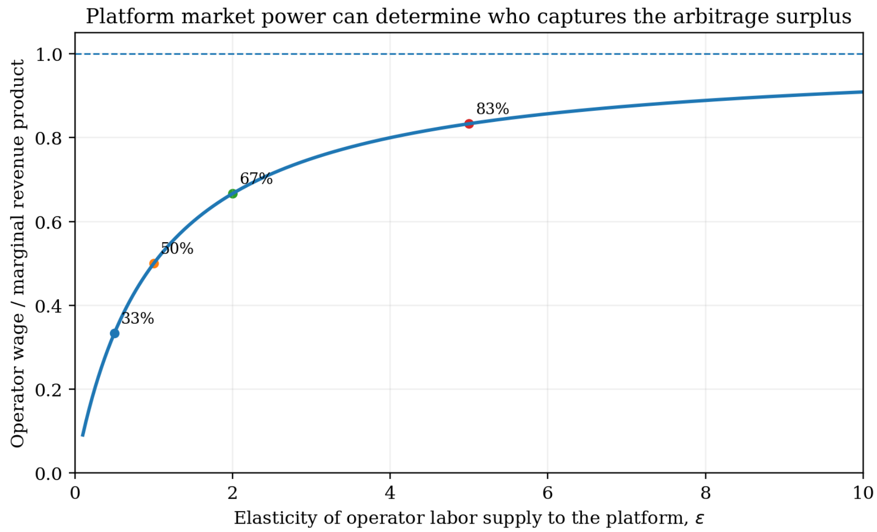

Figure 4: In the constant-elasticity monopsony example, the operator's share of marginal revenue product increases with the elasticity of labor supply to the platform.

6 Production geography and trade

6.1 Adding conventional offshore production

The baseline model compares destination labor with local robot capital controlled from abroad. Add a third option: conventional offshore physical production in the source country followed by shipment or delivery to the destination.

Let its unit cost be

$$c_O = w_S b + t \tag{18}$$

where b is source labor hours per unit and t includes shipping, inventory, coordination, tariffs, and the cost of locating the physical production stage abroad.

The firm now chooses the minimum of

$$\{c_H,\ c_O,\ c_E(z, A)\} \tag{19}$$

Remote embodiment differs from conventional offshoring because t is replaced by the network-control friction $\tau(z)$ and destination robot cost $r + w_H m$. It is favored when shipping or geographic separation of the physical production process is costly but transmission of control is relatively cheap.

6.2 Proposition 4: reshoring production while offshoring control

Proposition 4 (Hybrid reshoring). Consider a task initially produced offshore, so that

$$c_O < \min\{c_H, c_E(z, A_0)\}.$$

If autonomy rises from A_0 to A_1 or teleoperation friction falls such that

$$c_E(z, A_1) < c_O < c_H \tag{20}$$

then the physical production stage moves to the destination country while source-country labor remains employed through the positive operator input $h(A_1) > 0$.

This is **physical reshoring with labor-service offshoring**. Capital and output move toward the destination market, while control labor remains internationally supplied. A standard measure that records the location of the plant may classify the activity as reshored even though part of the labor value chain remains offshore.

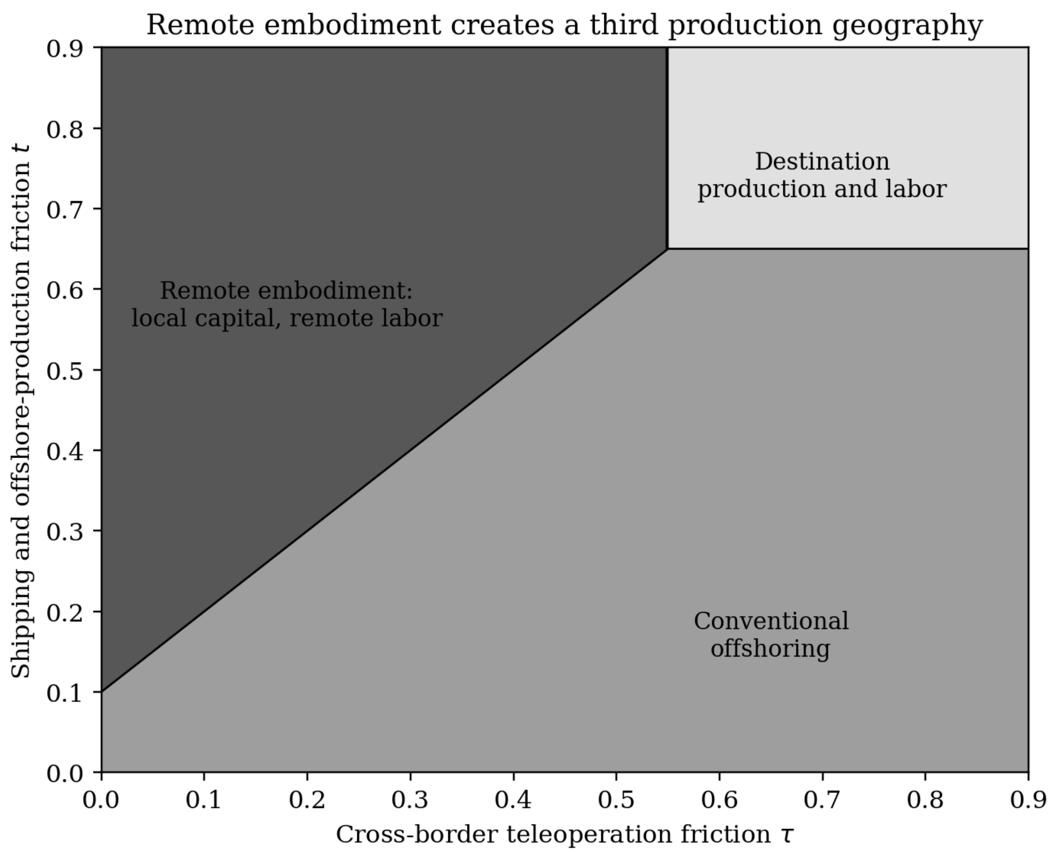

Figure 5: The least-cost production mode depends on both shipping frictions and teleoperation frictions. Remote embodiment occupies a distinct region in which capital is local and control labor is remote. Values are normalized and illustrative.

The result has three implications.

First, robot adoption need not imply a simple substitution of capital for all foreign labor. It can replace foreign physical production while retaining foreign control labor.

Second, remote embodiment can make destination production more resilient to shipping disruptions while creating a new dependence on networks, cloud infrastructure, cybersecurity, and foreign operator pools.

Third, trade statistics may record the imported input inconsistently. Depending on contracting structure, the remote labor component could appear as a business service import, a platform fee, an intra-firm service, or not be separately identified. Physical output statistics alone will not capture it.

7 Numerical illustration

This section illustrates the model's comparative statics with normalized parameters. It is not a market-size estimate or an empirical calibration.

Set destination unit labor cost to one: $w_H \ell = 1$. Let destination complementary labor cost be $w_H m = 0.08$, robot cost be $r = 0.38$, teleoperation friction be $\tau(z) = 0.70z$, and operator labor intensity be

$$h(A) = e^{-1.8A} \tag{21}$$

The cutoff is

$$z_c(A) = \frac{1 - 0.38 - 0.08 - w_S h(A)}{0.70} \tag{22}$$

bounded between zero and one.

At low autonomy, a source wage equal to one-half of the destination wage produces almost no remotely embodied tasks under these costs. A source wage equal to 15 percent of the destination wage supports a much larger set. As autonomy rises, the curves converge because operator labor becomes a smaller share of total cost. This is visible in Figure 2.

The convergence has an important interpretation. Labor arbitrage is most central when teleoperation is labor-intensive. As autonomy improves, robot and local-support costs dominate. The system becomes less sensitive to the source wage even as remote embodiment becomes feasible for more tasks. In the limit, the technology becomes ordinary automation and source-country operator demand approaches zero.

For source employment, suppose operator hours decline at rate γ and remotely embodied output grows at rate η:

$$h(A) = h_0 e^{-\gamma A}, \qquad Q_E(A) = Q_0 e^{\eta A} \tag{23}$$

Then

$$L_S^E(A) = h_0 Q_0 e^{(\eta - \gamma)A} \tag{24}$$

Figure 3 plots three cases. When $\eta < \gamma$, employment falls. When $\eta = \gamma$, employment is constant. When $\eta > \gamma$, employment rises despite increasing autonomy. The model therefore rejects a single unconditional prediction that teleoperation either creates or destroys source-country jobs.

The production-geography illustration normalizes costs to

$$c_H = 1, \qquad c_O = 0.35 + t, \qquad c_E = 0.45 + \tau \tag{25}$$

Low shipping friction favors conventional offshoring. Low teleoperation friction and sufficiently high shipping friction favor remote embodiment. When both frictions are high, destination labor remains least-cost. The exact boundaries are parameter-dependent, but the existence of a third region is general.

8 Empirical implementation

A credible empirical paper on remote embodiment requires data that do not yet exist in a standardized public form. This section specifies how the theory can be tested rather than substituting illustrative numbers for evidence.

8.1 Constructing a Remote Embodiment Potential Index

The first task is to measure ex ante exposure. Occupation-level telework indices are not sufficient because they classify physical-presence tasks as non-remote by construction. The relevant unit should be the detailed task.

For occupation o, define a Remote Embodiment Potential Index (REPI):

$$REPI_o = \sum_{k=1}^{K} \omega_k Z_{ok} \tag{26}$$

where Z_{ok} are standardized task characteristics and ω_k are weights estimated from observed technical feasibility or adoption.

Candidate characteristics include:

Model concept	Observable proxy
Observability	visual inspection content; need for hidden tactile state; camera coverage
Controllability	manual dexterity; force precision; tool and end-effector compatibility
Latency tolerance	required response time; pace determined by equipment; safety criticality
Reset intensity	frequency of jams, reloading, repair, cleaning, or scene rearrangement
Social locality	face-to-face interaction; assisting and caring for others; persuasion and trust
Standardization	repetition, task variance, workcell regularity, transferable procedures
Local complement	installation, maintenance, supervision, and physical-reset requirements

The current O*NET database provides occupation-level tasks, detailed work activities, abilities, and work-context measures that can seed the index (U.S. Department of Labor, Employment and Training Administration 2026). The weights should not be assigned entirely by judgment. They can be learned from task-level outcomes in teleoperation trials: completion rate, latency sensitivity, intervention duration, local-reset frequency, and commercial adoption.

The index should distinguish **continuous teleoperation potential** from **intervention potential**. A task may be uneconomic to control remotely for an entire shift but highly suitable for occasional recovery. These are different treatment intensities.

8.2 Firm-level event study

The cleanest direct design would use firm or establishment rollouts. Let T_f be the first date firm f deploys cross-border teleoperation. Estimate

$$y_{fit} = \alpha_f + \gamma_{it} + \sum_{k \neq -1} \beta_k \mathbf{1}[t - T_f = k] + X'_{fit}\delta + \varepsilon_{fit} \tag{27}$$

where i indexes industry and y includes:

- destination employment and wage bill by occupation;
- source-country operator hours and earnings;
- robot capital expenditure;
- output, task throughput, downtime, and labor productivity;
- imported service payments and platform fees;
- local maintenance and safety employment;
- human seconds per successful robot-hour.

Firm fixed effects absorb time-invariant differences and industry-by-time effects absorb common shocks. Event-study leads test for pre-trends.

The main identification challenge is endogenous adoption. Firms adopt after demand growth, labor shortages, process redesign, or successful pilots. Several instruments or quasi-experiments are plausible:

1. **Network-latency shocks.** New submarine cable routes, cloud regions, or routing changes alter source-destination latency. Interacting these shocks with pre-period task teleoperability can generate differential treatment intensity. RIPE Atlas provides geographically distributed latency measurements (RIPE Network Coordination Centre 2026).
2. **Exchange-rate shocks.** Source-country currency movements change operator cost in destination currency. Exposure can be interacted with pre-existing source-country operator shares.
3. **Robot-cost exposure.** Pre-period task composition can be interacted with global changes in the price or availability of compatible robot hardware.
4. **Platform entry.** Entry into a source labor market, opening of a training center, or certification rollout can change operator supply independently of a specific destination firm's demand.

Each design has limitations. Cable and cloud shocks can affect other digital inputs. Exchange rates may respond to macroeconomic conditions. Robot prices can be endogenous to sector demand. A strong study would combine several sources of variation and report reduced-form effects before imposing a structural interpretation.

8.3 Destination local labor markets

To study distributional effects, construct commuting-zone exposure:

$$Exposure_{ct} = \sum_{o} s_{co,0}\, REPI_o\, \Delta TeleopAdoption_{ot} \tag{28}$$

where $s_{co,0}$ is occupation o's pre-period employment share in location c. Outcomes include employment, wages, labor-force participation, occupational switching, migration, and establishment entry.

This follows the logic of prior trade- and robot-exposure designs but uses task-level remote-embodiment potential rather than import penetration or robot density. The key prediction is concentrated effects in occupations that combine high REPI with low local complementarity.

8.4 Source-country labor markets

Source-country analysis should distinguish gross job creation from wage incidence and job quality. Useful outcomes include:

- active operator hours and paid standby hours;
- hourly and annual earnings;
- wage premiums relative to local outside options;
- geographic diffusion beyond major cities;
- worker turnover and career progression;
- schedule alignment with destination time zones;
- social insurance and employment classification;
- exposure to monitoring and performance-based deactivation.

An event study around platform entry or training-center openings can compare treated labor markets with similar untreated locations. Worker-level panels can identify whether teleoperation raises total income or merely reallocates workers from other export-service jobs.

8.5 Data architecture

A useful research dataset would combine five layers:

1. **Robot session logs:** task, location, autonomous runtime, intervention frequency, handoff delay, recovery duration, local reset, and outcome.
2. **Operator records:** country, skill, pay, standby, active seconds, schedule, and platform history.
3. **Firm outcomes:** employment, wage bill, output, prices, capital expenditure, and service imports.
4. **Task characteristics:** O*NET measures, robot compatibility, safety, latency sensitivity, and REPI.
5. **Network conditions:** latency, jitter, packet loss, outages, and route changes.

The U.S. Census Bureau has collected establishment-level information on industrial robotic equipment and firm-level use of robotics and other advanced technologies, demonstrating that public statistical systems can measure technology adoption when survey instruments are designed for it (Acemoglu et al. 2022). A future module should distinguish autonomous robotics from continuous teleoperation, shared autonomy, and cross-border intervention.

8.6 Falsifiable predictions

The model produces testable predictions:

1. Adoption should be more sensitive to international wage gaps when human attention per robot-hour is high.
2. Improvements in autonomy should expand adoption while reducing operator minutes per robot-hour.
3. Source operator employment should rise only where fleet expansion exceeds the decline in attention intensity.
4. Destination employment losses should concentrate in high-REPI, low-complementarity tasks.
5. Local maintenance and safety employment should rise with embodied robot-hours.
6. Falling teleoperation friction should increase destination physical output and imported control services simultaneously.
7. Operator wage pass-through should be lower on platforms facing less elastic labor supply or weaker competition.

A paper that can test even the first four with firm and worker microdata would materially advance the economics of robotics.

9 Global economic implications

9.1 Expanding the tradability frontier

The first-order effect of remote embodiment is to turn some previously non-tradable physical tasks into traded services. The service crossing the border is a stream of observation, decision, and control. Its output is embodied locally by capital.

This can affect sectors historically insulated from service offshoring: warehousing, industrial inspection, machine tending, agriculture, infrastructure maintenance, security, logistics, and parts of construction. Exposure will remain task-specific. Tasks requiring local social presence, unobserved tactile information, immediate high-stakes response, or frequent physical resets may remain local for much longer.

A partial frontier shift can still matter. The trade and labor literature does not require all tasks in an occupation to become tradable for bargaining power, occupational composition, and location decisions to change. Firms can redesign jobs around the tasks that cross the network and leave residual local tasks to a smaller on-site workforce.

9.2 Wage convergence and segmentation

A globally accessible operator market creates pressure toward wage convergence, but several frictions prevent a single world wage:

- local outside options and labor supply elasticities;
- task-specific certification and language;
- latency and time-zone advantages;
- legal restrictions on where machines may be controlled;
- platform reputation and switching costs;
- currency risk and payment infrastructure;
- safety liability and insurance.

The likely outcome is segmented convergence. Source-country operators can earn a premium over local alternatives while remaining far below destination labor cost. Brinatti et al.'s evidence that remote digital wages remain tied to worker location is consistent with this structure (Brinatti et al. 2022).

As autonomy rises, wage sensitivity should fall because operator time becomes a smaller portion of total cost. Source locations may then compete more on reliability, skill, certification, and network quality than on wage alone.

9.3 Migration and services exports

Remote embodiment allows a worker to supply labor to a destination economy without migrating. For source countries, this creates a possible export category analogous to business-process services but attached to physical production.

The development impact depends on domestic capability formation. A low-road equilibrium would consist of fragmented, monitored, piece-rate intervention work with limited bargaining power. A higher-road equilibrium would build training, certification, fleet operations, safety management, robot integration, and locally owned platforms. The technology alone does not determine which equilibrium emerges.

The scale could remain modest if service-trade frictions, robot costs, and technical constraints remain high. Work on telemigration cautions that even large technological possibilities do not automatically create transformative service-export volumes (Baldwin and Dingel 2021). Remote embodiment should therefore be analyzed through observed adoption and trade flows rather than by multiplying all physical jobs by a wage ratio.

9.4 Destination productivity and adjustment

Destination firms can benefit through lower unit cost, longer operating hours, reduced exposure to local labor shortages, and faster deployment of imperfectly autonomous robots. Consumers can benefit if competition passes cost reductions through to prices.

The losses may be concentrated. A worker displaced from a locally bound physical task may have made education and location choices under the assumption that the task could not be offshored. Adjustment costs can therefore be larger than aggregate models imply. Prior trade shocks show that labor mobility and re-employment can be slow (Autor, Dorn, and Hanson 2016).

Remote embodiment also creates local complements. Robots require installation, maintenance, workcell redesign, safety systems, local emergency response, and site-specific operations. The net destination employment effect depends on the labor intensity of these complements and the expansion of output.

9.5 Dynamic transition to automation

The most distinctive dynamic effect is that remote labor can generate data that improves autonomy. Intervention logs identify the states in which a policy fails and the actions that recover the task. This creates a feedback loop:

$$\text{deployment} \to \text{human intervention} \to \text{recovery data} \to \text{better policy} \to \text{lower } h(A).$$

Source-country labor is therefore both a current production input and a potential input into its own future substitution. Whether operators share in the resulting productivity gains depends on ownership of the data, portability of reputation, profit sharing, and the creation of higher-skill tasks.

This dynamic can produce a lifecycle:

1. **labor-arbitrage phase:** one remote worker controls one robot;
2. **leverage phase:** one worker supports several robots through sparse intervention;
3. **training phase:** recurring recoveries are learned from operator data;
4. **tail phase:** humans handle only novel or high-risk cases.

The length of each phase is an empirical question. The model predicts that source employment can rise in the leverage phase and fall in the tail phase.

9.6 Security and systemic dependence

Remote embodiment replaces some shipping dependence with network dependence. Destination production may become more geographically local yet operationally reliant on foreign labor pools, cloud infrastructure, identity systems, and communication routes.

The resulting risks include cyber intrusion, credential theft, correlated platform outages, cable disruption, sanctions, cross-border data restrictions, and malicious control. These risks enter the model through $\tau(z)$ and expected failure cost, but their policy importance exceeds a simple unit-cost term. Critical infrastructure may face domestic-control requirements even when foreign operation is cheaper.

10 Policy and measurement

The appropriate policy response is not to classify remote embodiment as either ordinary outsourcing or ordinary automation. It combines elements of trade, capital regulation, labor platforms, cybersecurity, and workplace safety.

10.1 Statistical classification

Statistical agencies should separately measure:

- the physical location of the robot and output;
- the location of the operator;
- whether control is continuous, shared, or intervention-based;
- operator seconds and standby time per robot-hour;
- payments to operators, platforms, and local support workers;
- the ownership location of the robot, software, and intervention data.

Without this decomposition, reshoring statistics can overstate the return of labor demand, and services-trade statistics can miss the physical output enabled by imported control.

10.2 Labor standards

Cross-border operation creates ambiguity about the employer, worksite, and jurisdiction. Minimum standards should assign responsibility for safety, training, wages, fatigue, data use, and incident investigation. Pay rules should account for mandatory standby and not only active control seconds. Operators should have access to performance records and meaningful appeal processes when automated systems suspend or rank them.

These concerns are extensions of existing platform-work issues documented by the ILO and World Bank (International Labour Office 2021; Datta et al. 2023), but the physical consequences of an operator error make accountability more urgent.

10.3 Competition and portability

Platform concentration can lower operator wage pass-through and allow intermediaries to capture data generated by worker interventions. Portable certifications, interoperable control standards, and exportable performance histories can increase labor supply elasticity to any single platform and reduce the markdown in Proposition 3.

Customers should also retain access to task and intervention logs in standardized formats. Data portability can reduce lock-in and permit multiple providers to compete on safety, routing, and recovery quality.

10.4 Adjustment policy

Destination policy should focus on exposed workers and places rather than attempting to preserve every task. Training should be tied to complementary roles such as robot maintenance, field service, safety, installation, and process engineering. Wage insurance and mobility support may be more relevant than generic digital-skills programs.

Source-country policy should aim beyond low wages. Reliable connectivity, operator certification, domain specialization, formal employment, and career paths into fleet supervision and robotics operations can convert a temporary arbitrage into capability accumulation.

11 Conclusion

Remote teleoperation changes the economic meaning of distance for physical work. A destination robot can embody labor supplied from another country, allowing control to cross a border while capital and output remain local.

The task-based model yields four conclusions.

First, the international wage gap interacts with robot cost, autonomy, and network friction to determine a tradability cutoff. Remote embodiment does not globalize all physical work; it expands the eligible task set at the margin.

Second, autonomy has opposing effects on source-country labor. It reduces human attention per robot-hour while expanding the number of tasks and deployments for which remote embodiment is economical. Operator employment rises only when scale grows faster than labor intensity falls.

Third, production geography is no longer a binary choice between domestic production and offshoring. A firm can reshore physical capital and output while continuing to import the labor service that controls them.

Fourth, the distribution of gains is institutional. Platform competition, labor supply elasticity, data ownership, and worker protection determine whether the arbitrage surplus flows to operators, consumers, or capital owners.

The most important empirical variable is therefore not whether a robot is described as autonomous. It is

human seconds per successful robot-hour,

measured together with the location and compensation of those human seconds.

The first large global effect of general-purpose robotics may not be the immediate disappearance of physical labor. It may be the conversion of physical action into a cross-border service, followed by the gradual automation of that service.

12 Appendix A: proofs

12.1 Proof of Proposition 1

The cutoff is implicitly defined by

$$F(z_c, A, w_H, w_S, r) = r + w_H m + w_S h(A) + \tau(z_c) - w_H \ell = 0.$$

Since $F_z = \tau'(z_c) > 0$, the implicit function theorem gives

$$\frac{\partial z_c}{\partial A} = -\frac{F_A}{F_z} = -\frac{w_S h'(A)}{\tau'(z_c)} > 0,$$

because $w_S > 0$ and $h'(A) < 0$. Similarly,

$$\frac{\partial z_c}{\partial w_H} = -\frac{m - \ell}{\tau'(z_c)} = \frac{\ell - m}{\tau'(z_c)} > 0,$$

$$\frac{\partial z_c}{\partial w_S} = -\frac{h(A)}{\tau'(z_c)} < 0, \qquad \frac{\partial z_c}{\partial r} = -\frac{1}{\tau'(z_c)} < 0.$$

This proves the proposition. □

12.2 Proof of Proposition 2

By definition, $L_S^E(A) = h(A)Q_E(A)$. Taking logarithms and differentiating gives

$$\frac{d \ln L_S^E}{dA} = \frac{h'(A)}{h(A)} + \frac{Q_E'(A)}{Q_E(A)}.$$

Since $h'(A) < 0$, employment increases if and only if

$$\frac{Q_E'(A)}{Q_E(A)} > -\frac{h'(A)}{h(A)}.$$

This is equation (13). □

12.3 Proof of Proposition 3

The platform maximizes

$$\Pi(w) = (v - w)\overline{L}w^{\varepsilon}.$$

The first-order condition is

$$-\overline{L}w^{\varepsilon} + (v - w)\overline{L}\varepsilon w^{\varepsilon-1} = 0.$$

Dividing by $\overline{L}w^{\varepsilon-1}$ gives

$$-w + \varepsilon(v - w) = 0,$$

so

$$(1 + \varepsilon)w = \varepsilon v \quad \Rightarrow \quad w = \frac{\varepsilon}{1 + \varepsilon}v.$$

This proves the proposition. □

12.4 Proof of Proposition 4

At A_0, conventional offshore production is strictly least-cost. By assumption, at A_1 the remote-embodiment cost falls below c_O while $c_O < c_H$. Therefore $c_E(z, A_1)$ is strictly below both alternatives, and the firm locates the robot and physical production stage in the destination. Since $h(A_1) > 0$, source-country labor remains an input. □

13 Appendix B: proposed task-level variables

Category	Example measure	Predicted sign for REPI
Visual observability	task state visible from fixed and wrist cameras	Positive
Hidden tactile dependence	force or texture information unavailable remotely	Negative
Manual dexterity	precision and degrees of freedom required	Ambiguous; depends on hardware
Response speed	need for immediate reaction	Negative
Repetition	frequency of similar action sequences	Positive
Workcell regularity	stable layout and known object set	Positive

Category	Example measure	Predicted sign for REPI
Local reset frequency	jams, refills, repairs, and cleaning	Negative
Human proximity risk	severity of remote-control error around people	Negative
Social interaction	caring, persuasion, reassurance, and trust	Negative
Tool compatibility	task can be performed with available end effectors	Positive
Shared-autonomy support	low-level stabilization or grasp assistance available	Positive
Network quality	low latency, jitter, and packet loss for the route	Positive

The REPI should be validated against observed task completion, quality, safety, and cost rather than treated as a purely subjective ranking. A useful estimation target is the probability that remote embodiment has lower quality-adjusted unit cost than destination labor for a given task and source-destination pair.

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