Technology Rivalry and Resilience Under Trade Disruptions: The Case of Semiconductor Foundries

Weiting Miao

Stanford University

Motivation & Research Question

Motivation

- Rising concerns about trade disruptions
- Recent surge in industrial policies in the semiconductor industry, e.g., US CHIPS and Science Act (2022)
    - 25% investment subsidy $\Rightarrow$ Local supply resilience
    - Investment restrictions in mainland China (CN) $\Rightarrow$ Technology leadership

Research Questions

How does industrial policy affect:

- Firms' innovation and capacity investment across locations in oligopolistic industries
- Technology race across countries and local consumer welfare in the face of trade disruption risks

This Paper

1. A dynamic oligopoly model of innovation and multi-location production
   - Trade disruption risks + industrial policies

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2. Estimate the model using micro-level data in semiconductor foundries
   - Price and quantity by technology $\implies$ demand curves
   - Capacity, technology, and investment cost $\implies$ firm-level productivity, production and R&D costs

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   - Trade disruption risks + industrial policies

2. Estimate the model using micro-level data in semiconductor foundries
   - Price and quantity by technology $\implies$ demand curves
   - Capacity, technology, and investment cost $\implies$ firm-level productivity, production and R&D costs

3. Quantify the impacts of US CHIPS Act
   - Capacity investment subsidies
   - Investment restrictions

Institutional Background
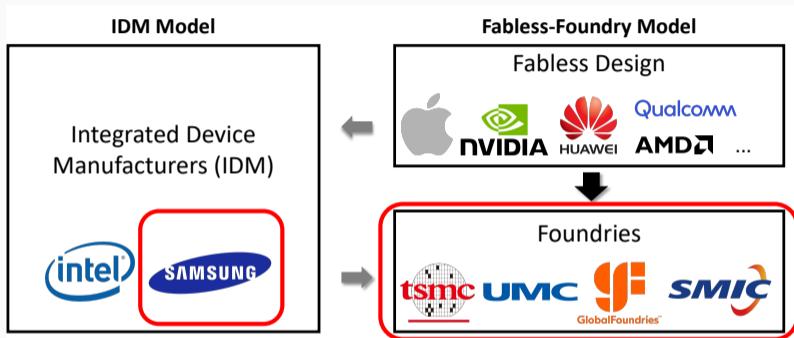
- Focus on foundries for advanced logic ICs
- Mainly used in smartphones, PCs, and high performance computing platforms
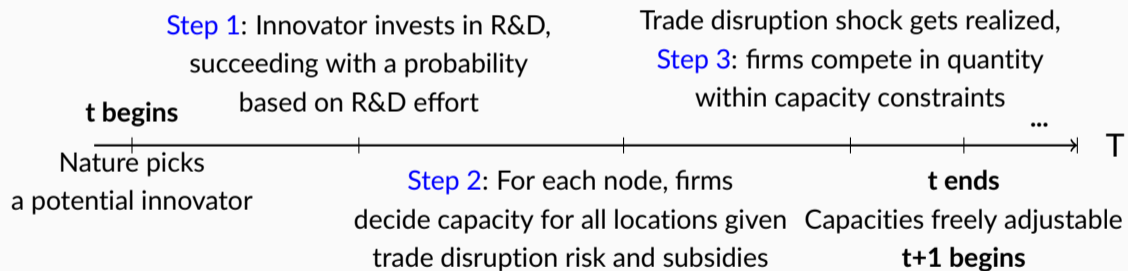- Identify technology vintage by process node (e.g., 3nm, 5nm, 7nm)

Supply Demand Imbalance Across Regions

Industry Features Summary

	Industry Features	Model Assumption
Market Structure Details	Limited number of firms	Oligopoly competition
Nature of Innovation Details	Leapfrogging is rare	Step-by-step innovation
Cost Structure Details	High R&D Intensity	Focus on R&D and capacity decisions
	Equipment cost dominates	Capacity investment subsidies as the policy tool

A dynamic oligopoly model of innovation and multi-location production

- Technology ladder from generations 1 to $\bar{N}$, firms can produce multiple vintages

t begins

Nature picks
a potential innovator

Step 1: Innovator invests in R&D,
succeeding with a probability
based on R&D effort

Step 2: For each node, firms
decide capacity for all locations given
trade disruption risk and subsidies

Trade disruption shock gets realized,
Step 3: firms compete in quantity
within capacity constraints

...

t ends

Capacities freely adjustable
t+1 begins

T

- Trade disruption $\Rightarrow$ can only serve customers within local capacity

How Firms Make Decisions

- Capacity building across locations
  - Investment cost: affected by local subsidies
  - Market access: exposed to trade risk

How Firms Make Decisions

- Capacity building across locations
  - Investment cost: affected by local subsidies
  - Market access: exposed to trade risk

- R&D investment
  - Cost: depends on technology spillover (followers face lower unit costs than the leader)
  - Benifit: profits from current technology + option value from future technologies

Step 3: Optimal Shipment Decisions

- The expected profit given capacity and trade disruption risk ψ is (abstract from node n and time t)

$$\pi_i(\mathbf{C}_i, \mathbf{C}_{-i}, \psi) = \max_{q_{i,int}, \{q_{im}\}_{m=1}^M} (1-\psi) \underbrace{\pi_{i,int}(q_{i,int}, q_{-i,int})}_{\text{unified global market}} + \psi \underbrace{\sum_m \pi_{im}(q_{im}, q_{-im})}_{\text{segmented local markets}}$$

$$\text{s.t. } q_{i,int} \leq C_{i,int} = \sum_m C_{im}, \ q_{im} \leq C_{im} \ \forall m$$

- $\mathbf{C}_i$: vector of firm i's capacities across all locations
- C_{im}, q_{im}: i's capacity/shipment quantity in market m
- $q_{i,int}, C_{i,int}$: i's global capacity/shipment quantity

- With shipment unit cost $= 0$ and price elasticity > 1, firms use full capacity

Capacity Installation Problem

- Given the unit cost of capacity at each location κ_{im}, firms install the optimal capacity at each location

$$\max_{C_{im} \geq 0} \pi_i(\mathbf{C}_i, \mathbf{C}_{-i}, \psi) - \sum_m \kappa_{im} C_{im}$$

- κ_{im} depends on the investment subsidies

$$\kappa_{im} = \delta_{im} \frac{w_m}{\nu_i} (1 - s_m)$$

  - δ_{im}: foreign cost shifter
  - w_m: fundamental cost at production location, ν_i: firm-level productivity
  - s_m: investment subsidy rate

Step 2: Optimal Capacity Installation

$$(1 - \psi) \left(\underbrace{\frac{\partial P_{int}}{\partial Q_{int}} \sum_m C_{im}^* + P_{int}}_{\text{same across all locations}} \right) + \psi \left(\underbrace{\frac{\partial P_m}{\partial Q_m} C_{im}^*}_{\text{price effect}} + \underbrace{P_m}_{\text{quantity effect}} \right) = \kappa_{im} \ \forall i, m$$

- When $\psi = 0$: concentrate capacity in the most efficient location
- When $\psi > 0$: diversify capacity
- When $1 > \psi > 0$: $s_m \uparrow \implies \kappa_{im} \downarrow \implies C_{im}^* \uparrow \implies C_{im'}^* \downarrow, \forall m' \neq m$

TSMC's Production Expansion

Innovator's R&D Investment

$$V_{it}(S_t) = \pi_{it}(S_t) + \max_{d \geq 0} \left\{ -c_{i,d}(S_t)d + \beta \left[\begin{array}{l} \rho(d)\tilde{V}_{it}^{success}(S_{t+1} \mid S_t) \\ +(1 - \rho(d))\tilde{V}_{it}^{fail}(S_{t+1} \mid S_t) \end{array} \right] \right\}$$

State variables: S_t

- $\bar{n}_t \leq \bar{N}$: the frontier technology
- $\Delta n_{it} \in \{0, 1, 2, \text{exit}\}$: the lag between firm i's leading technology and $\bar{n}_t$, $\forall i$
- $q_t \leq \bar{q}$: age of the frontier technology; $\{D_{nt}\}_{t=0}^{\infty}, \forall n$: other demand shifters
- $\{s_{nmt}\}_{t=0}^{\infty}, \forall n, m$: trajectories of local subsidies

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Innovation unit cost

- $c_{i,d}(S_t) = c_0(1 + g^c)^{(\bar{n}_t - \Delta n_{it})}\gamma^{1(\Delta n_{it} > 0)}$
- $\gamma < 1$, capturing across-firm technology spillover

R&D Details

- FOC implies optimal R&D level, conditioned on it being positive

$$c_{i,d}(S_t) = \beta \rho'(d_i^*) \underbrace{\left[\ \tilde{V}_{it}^{success}(S_{t+1} \mid S_t) - \tilde{V}_{it}^{fail}(S_{t+1} \mid S_t) \ \right]}_{\Lambda_{it}^{gap}(S_t)}$$

- $s_{nm} \uparrow \implies \Lambda_{it}^{gap}(S_t) \uparrow \implies d_i^* \uparrow$

Industry Equilibrium   Non-innovator's Value   Backward Induction   Two-Firm Illustration

Market Inefficiency on Optimal Subsidy

- Inefficiencies
  - Oligopoly competition $\implies$ market power distortion $\implies$ inefficiently small capacity
  - Followers have lower R&D cost $\implies$ technology externalities $\implies$ inefficiently low R&D

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  - Benefits leak abroad but local taxpayers pay all policy costs $\implies$ low optimal subsidy rate

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- With trade disruption
  - Firms internalize the risk but still subject to inefficiencies
  - Trade disruption probability $\uparrow$ $\implies$ benefit and cost are more closely aligned $\implies$ optimal subsidy rate $\uparrow$

Technology Competition: Integrated vs. Separated Markets

- Far-behind firms have weak incentives to innovate in an integrated market
  - Low price for new generation: leaders already compress markups
  - Low option value: low chance of becoming the leader
  - Subsidies have limited impact: also spur rivals to innovate to avoid being overtaken

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  - Subsidies have limited impact: also spur rivals to innovate to avoid being overtaken
- In separated markets with FDI banned, globally lagging but locally leading firms have strong R&D incentives
  - Local leaders can capture high markups on new generations and the option value of future leadership
  - Subsidies are much more effective for these firms

Estimation

Assume no trade disruption risk during the sample period

Estimation Steps

Step	Data	Method
Demand	Price & quantity by technology Downstream shipment by location	IV regression Estimated α_D & model structure
Capacity Cost	Equipment cost by technology Firm capacity/revenue share	Log Regression First-order condition
R&D Cost	TSMC R&D cost trend Technology upgrading history	Log Regression Maximum likelihood

Estimation Results Highlights

- US and CN: 25% and 22% of global demand
- TSMC: 50%+ more productive than competitors
- Lagging firms: 22% of R&D unit costs of leaders

Counterfactual Analysis Roadmap: Capacity Investment Subsidies

Motivated by the US CHIPS Act

- Unilateral Investment Subsidies in the US
  - Two firms: TSMC and Samsung
  - Capacity investment subsidies for fabs built in the US
  - Compare consumer surplus and policy costs
  - **Static benefits** from resilience and offsetting market power and **dynamic benefits** from accelerated innovation
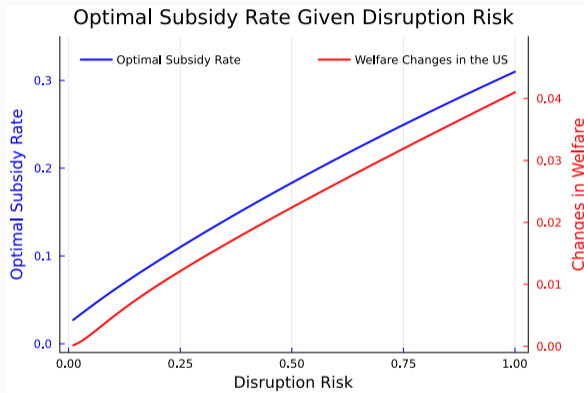- Investment Restrictions in mainland China

Static Gains in the US
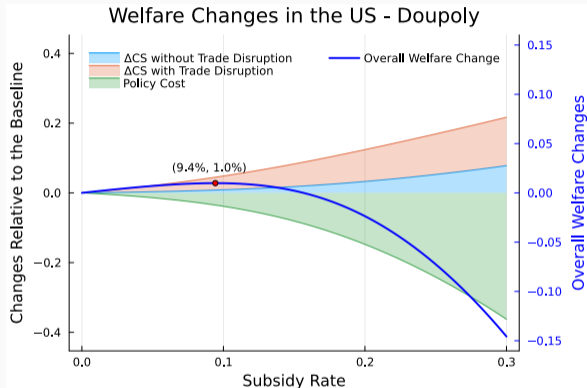
Welfare Changes in the US - Doupoly

Baseline case: 2 incumbents, $\delta = 1.0$ (foreign cost shifter), $\psi = 0.2$ (trade disruption risk)

- Capacity investment subsidies reduce prices, at a policy cost, with or without trade disruption

Static Gains in the US

Optimal Subsidy Rate Given Disruption Risk

Baseline case: 2 incumbents, $\delta = 1.0$

Monopoly Case   Foreign Cost Shifter δ Static Gains in Other Locations

- Capacity investment subsidies reduce prices, at a policy cost, with or without trade disruption

- Optimal subsidy rate increases with disruption risk

Dynamic Gains in the US

Welfare Changes in the US
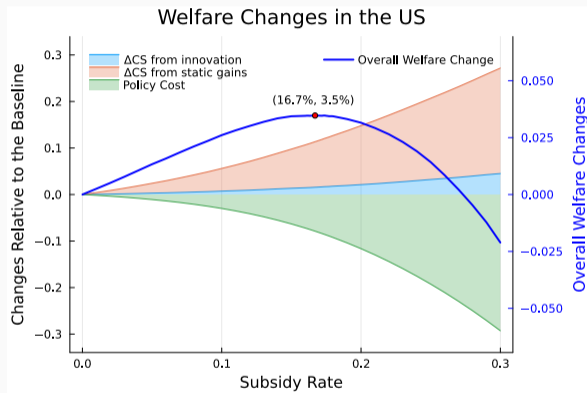
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- Dynamic innovation gains further justify the subsidy, but the main benefits are static

Dynamic Gains in the US

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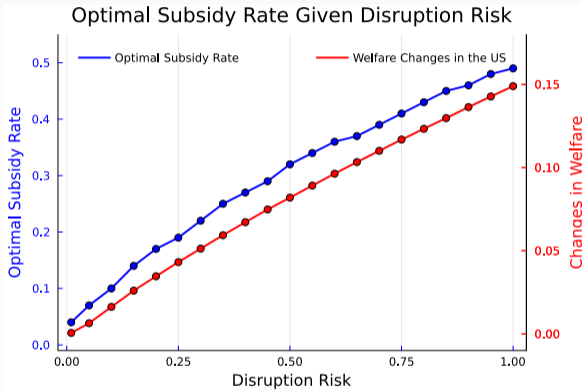
Setting: $\delta = 1.0$

Frontier Technology with and without Subsidies   No Disruption Risk Case

- Dynamic innovation gains further justify the subsidy, but the main benefits are static

- Lower optimal subsidy rate and smaller welfare gains when trade disruption risk is low

Welfare Implication in Other Locations

Welfare Changes in Other Locations

Baseline case: $\delta = 1.0, \psi = 0.2$

- Improve instead of harm welfare in other locations

Welfare Changes in Other Locations
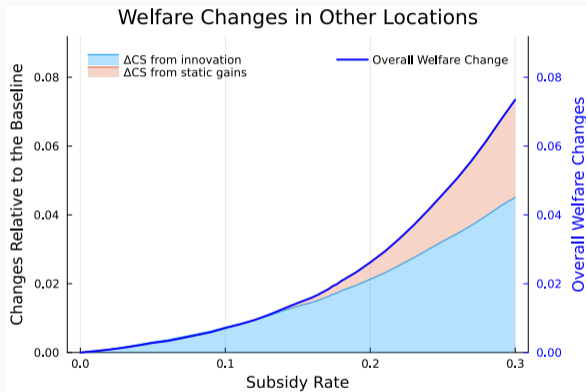
Baseline case: $\delta = 1.0, \psi = 0.2$

- Improve instead of harm welfare in other locations
- The majority of welfare gains comes from the innovation channel

- Unilateral Investment Subsidies in the US
- Investment Restrictions in mainland China
    - Three firms: TSMC, Samsung, and SMIC (national champion)
    - TSMC and Samsung cannot expand capacity in CN
    - Lower technology spillover between SMIC and others $\Rightarrow \alpha \geq 1$ captures the technology blocking effect magnitude
    - Compare tech trajectories with/without restrictions
    - **Higher profit** from secured market demand vs. **higher R&D cost** from weaker technology spillover (Details)
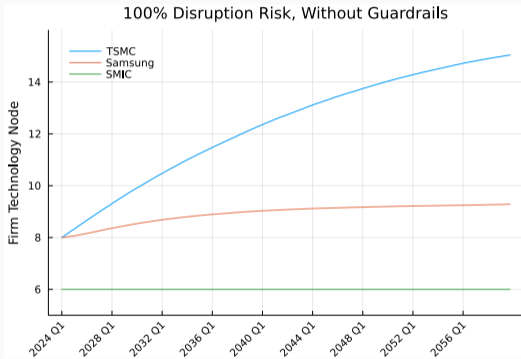
20% Trade Disruption Risk

Simulated Firm Technology Trajectories: Without Guardrails

20% Disruption Risk, With Guardrails, $\alpha = 1.0$
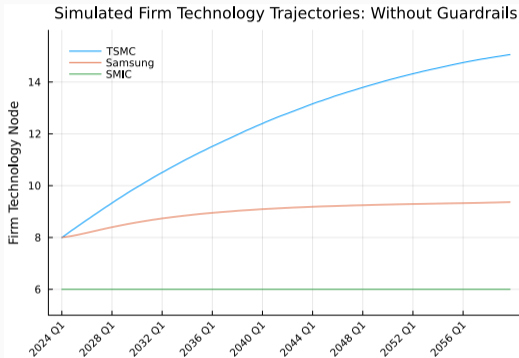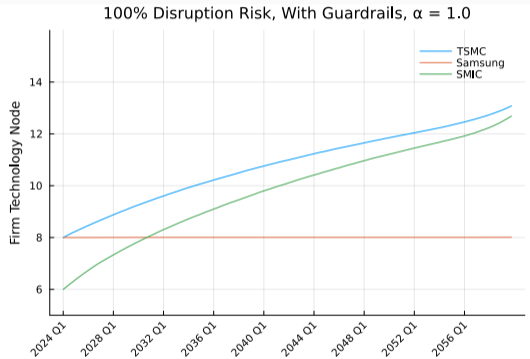
Without Guardrails: $\psi = 20\%$
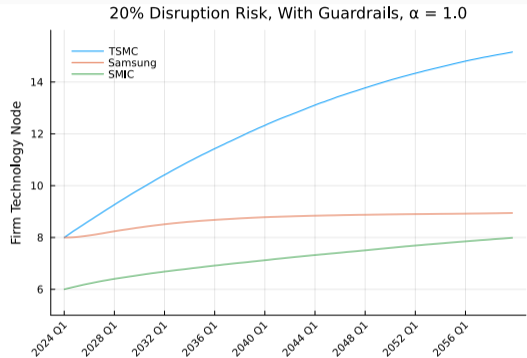
With Guardrails: $\psi = 20\%, \alpha = 1.0$

- Market demand securing is weak when disruption risk is low
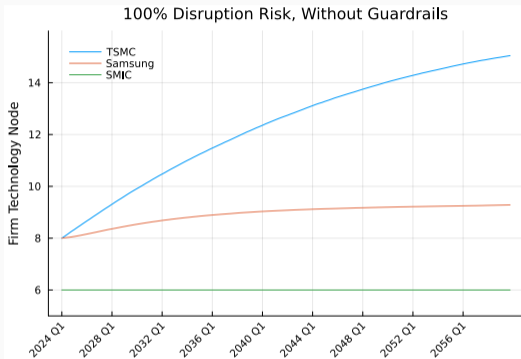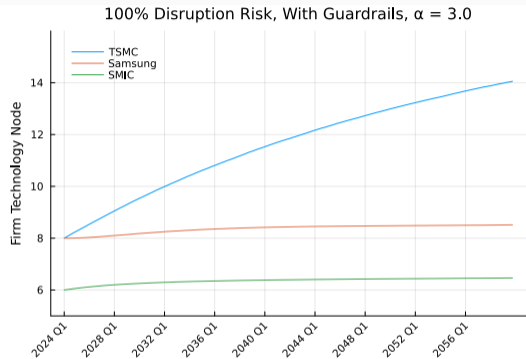
100% Trade Disruption Risk

100% Disruption Risk, Without Guardrails

100% Disruption Risk, With Guardrails, α = 1.0

Without Guardrails: $\psi = 100\%$

With Guardrails: $\psi = 100\%, \alpha = 1.0$

100% Trade Disruption Risk

100% Disruption Risk, Without Guardrails

100% Disruption Risk, With Guardrails, α = 3.0

Without Guardrails: $\psi = 100\%$

With Guardrails: $\psi = 100\%, \alpha = 3.0$

- A spillover reduction factor of 3 is needed to prevent SMIC's technology from advancing with guardrails, i.e., $\lambda : 22\% \rightarrow 66\%$

Conclusion & Future Extension

- A dynamic oligopoly model with step-by-step innovation, multi-location production, trade disruption risks, and industrial policies
- Impacts of US CHIPS Act
  - Trade disruption risk $\uparrow \implies$ optimal capacity investment subsidies $\uparrow$
  - Investment restrictions in CN might $\uparrow$ CN firms' innovation
- Future Extension
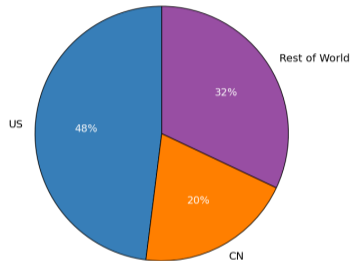 - Unilateral policy analysis $\implies$ Subsidy race

Additional Material

Two-Firm Illustration

Supply Demand Imbalance
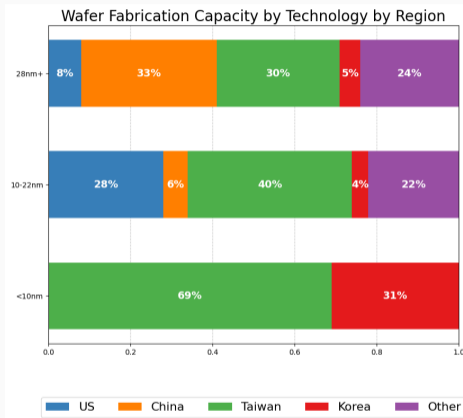
Source: BCG; Omdia data in 2023 Q4 and author's calculation

- Notable imbalance between foundry capacity and demand across locations

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Decreasing Number in Leading-Edge Manufacturers Over Time
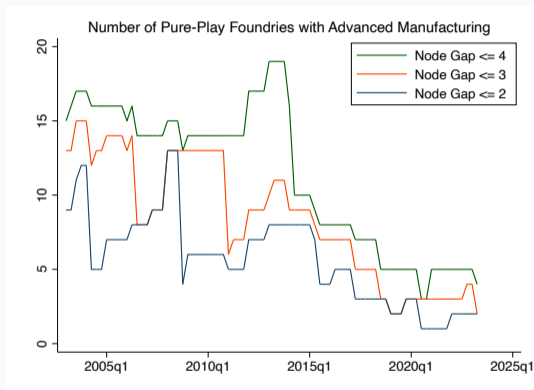
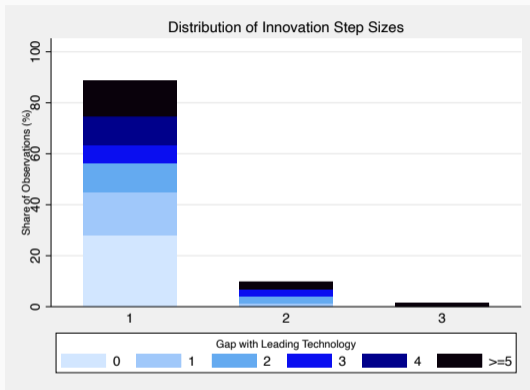**Source:** Omdia data and author's calculation

- Highly concentrated and continues to intensify Include IDM   Back

Incremental Innovation
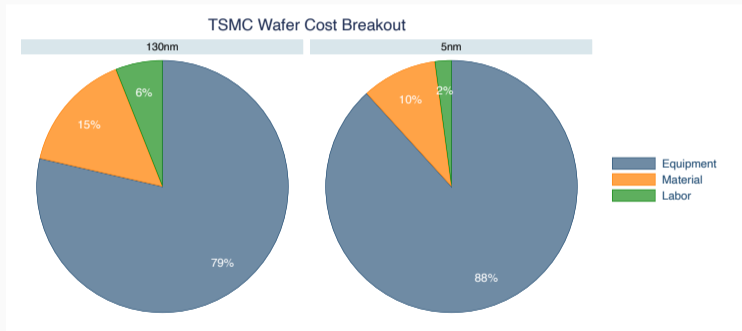

Source: Omdia data and author's calculation

- Leapfrogging is rare and mostly happens in mature nodes
- No new firms directly competing in advanced nodes
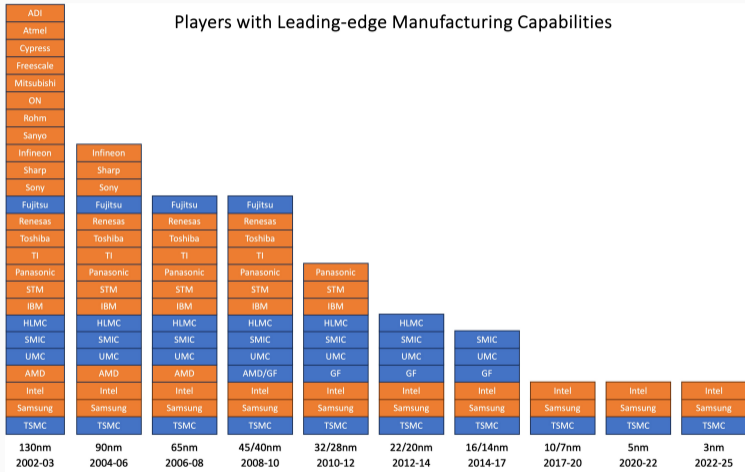
High R&D Intensity & Equipment Cost Dominates

- High R&D intensity: $\sim$ 10% of sales
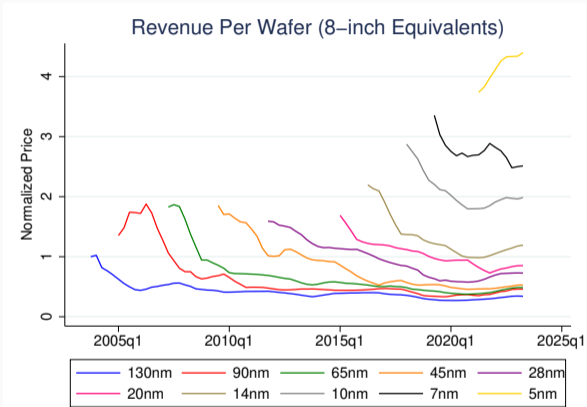- Equipment costs account for the majority of wafer cost

Source: IC Knowledge Strategic Cost Model and author's calculation

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Industry Evolution including IDMs

Players with Leading-edge Manufacturing Capabilities

130nm 2002-03	90nm 2004-06	65nm 2006-08	45/40nm 2008-10	32/28nm 2010-12	22/20nm 2012-14	16/14nm 2014-17	10/7nm 2017-20	5nm 2020-22	3nm 2022-25
ADI									
Atmel									
Cypress									
Freescale									
Mitsubishi									
ON									
Rohm									
Sanyo									
Infineon	Infineon								
Sharp	Sharp								
Sony	Sony								
Fujitsu	Fujitsu	Fujitsu	Fujitsu						
Renesas	Renesas	Renesas	Renesas						
Toshiba	Toshiba	Toshiba	Toshiba						
TI	TI	TI	TI						
Panasonic	Panasonic	Panasonic	Panasonic	Panasonic					
STM	STM	STM	STM	STM					
IBM	IBM	IBM	IBM	IBM					
HLMC	HLMC	HLMC	HLMC	HLMC	HLMC				
SMIC	SMIC	SMIC	SMIC	SMIC	SMIC	SMIC			
UMC	UMC	UMC	UMC	UMC	UMC	UMC			
AMD	AMD	AMD	AMD/GF	GF	GF	GF			
Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel
Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung
TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC

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Frontier Firms Gain Higher Profits

Revenue Per Wafer (8–inch Equivalents)

Source: Omdia data and author's calculation

- Price drops rapidly after introduction

Frontier Firms Gain Higher Profits

| | Unit Investment Cost | | | |
	(1)	(2)	(3)	(4)
Time Trend	0.0002	0.0006	0.0016	0.0004
	(0.0007)	(0.0006)	(0.0012)	(0.0010)
Log(Capacity)		-0.0253*	-0.0186	-0.0079
		(0.0132)	(0.0107)	(0.0128)
Constant	0.1779***	0.4347***	0.3509**	0.2554*
	(0.0131)	(0.1366)	(0.1202)	(0.1274)
Technology Node Fixed Effects	Yes	Yes	Yes	Yes
Firm Fixed Effects	No	No	Yes	No
Country Fixed Effects	No	No	No	Yes
N	107	107	97	106
R^2	0.9038	0.9082	0.9233	0.9227

Source: SEMI data and author's calculation

- Price drops rapidly after introduction
- Investment cost of fixed nodes doesn't decrease significantly over time

Frontier Firms Gain Higher Profits

Operating Margin of Top 4 Pure-Play Foundries
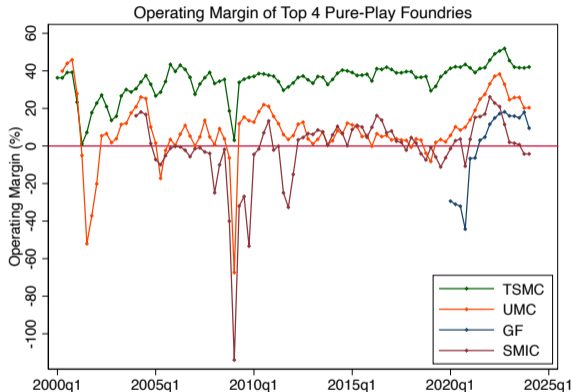
- Price drops rapidly after introduction
- Investment cost of fixed nodes doesn't decrease significantly over time
- **Frontier firms gain high profits**

Source: Firms' quarterly reports and author's calculation

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Trade Disruption Shock Examples

- Export controls / Sanctions
- Pandemic crises leading to restrictions on the movement of goods
- Risks causing disruptions in shipping and logistics

Microfoundation of the Demand Curve

- Consumers demand goods from multiple sectors with preferences

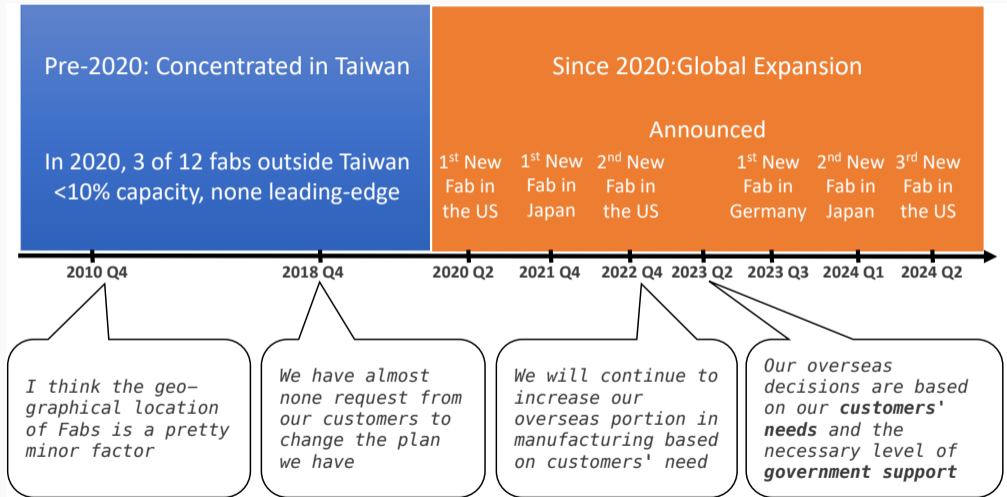$$U_m = \Pi_s (c_m^s)^{\beta^s} \text{ where } \sum_s \beta^s = 1$$

- Each sector requires a specific generation of chips and a homogeneous and freely tradable numeraire good

$$c_m^s = q_0 + \exp\left(\frac{\alpha_0^s}{\alpha_p}\right) \frac{q_c^{s\,1-\frac{1}{\alpha_p}}}{1 - \frac{1}{\alpha_p}}$$

- The demand for a specific generation of chip is given by

$$\log(q_c^s) = \alpha_0^s - \alpha_p \log(p_c^s)$$

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TSMC's Production Expansion

Pre-2020: Concentrated in Taiwan

In 2020, 3 of 12 fabs outside Taiwan <10% capacity, none leading-edge

Since 2020: Global Expansion

Announced

| 1st New Fab in the US | 1st New Fab in Japan | 2nd New Fab in the US | 1st New Fab in Germany | 2nd New Fab in Japan | 3rd New Fab in the US |

2010 Q4 — 2018 Q4 — 2020 Q2 — 2021 Q4 — 2022 Q4 — 2023 Q2 — 2023 Q3 — 2024 Q1 — 2024 Q2

I think the geographical location of Fabs is a pretty minor factor

We have almost none request from our customers to change the plan we have

We will continue to increase our overseas portion in manufacturing based on customers' need

*Our overseas decisions are based on our **customers' needs** and the necessary level of **government support***

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Innovator's R&D Investment Details

Bellman Equation

- $V_{it}(S_t)$: innovator's value
- $W_{it}^j(S_t)$: non-innovator's value when j is picked as the innovator
- $\Lambda_{it}(S_t)$: expected value before knowing the innovator

$$V_{it}(S_t) = \pi_{it}(S_t) + \max_{d \geq 0} \left\{ -c_{i,d}(S_t)d + \beta \left[\begin{array}{c} \rho(d)[\Lambda_{it+1}(S_{t+1} \mid S_t, a_{it} = 1) \\ +1(\bar{n}_{t+1} > \bar{n}_t)\pi_{it}^{n=2}(S_t)/(1-\beta)] \\ +(1-\rho(d))\Lambda_{it+1}(S_{t+1} \mid S_t, a_{it} = 0) \end{array} \right] \right\}$$

- d: innovation effort; $\rho(d) = \frac{d}{1+d}$: probability of successful R&D; $a_{it} = 1$ if the R&D is successful
- $\pi_{it}^{n=2}(S_t)$: profit from a node two generations behind the frontier Back

Non-Innovator's Value and Ex-ante Value

- Non-innovator's value when j is picked as the innovator

$$W_{it}^{j}(S_t) = \pi_{it}(S_t) + \beta \left[\begin{array}{c} \rho(d_j^*(S_t))[\Lambda_{it+1}(S_{t+1} \mid S_t, a_{jt} = 1) \\ + \mathbb{1}(\bar{n}_{t+1} > \bar{n}_t)\pi_{it}^{n=2}(S_t)/(1-\beta)] \\ + \left[1 - \rho(d_j^*(S_t))\right] \Lambda_{it+1}(S_{t+1} \mid S_t, a_{jt} = 0) \end{array} \right]$$

- Expected value before knowing the innovator

$$\Lambda_{it}(S_t) = p_{pick} \left[V_{it}(S_t) + \sum_{j \neq i} W_{it}^{j}(S_t) \right]$$

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Industry Equilibrium

A sequential industry equilibrium is a set of functions
$V_{it}(S_t), W_{it}(S_t), \Lambda_{it}(S_t), d_{it}^*(S_t), C_{inmt}^*(S_t), q_{inmt}^*(\mathbf{C}_{nmt}, \mathbf{1}(\Psi_t < \psi)), P_{nmt}(\mathbf{q}_{nmt}^*)$
such that for each firm i and period $t \leq T$

- $V_{it}(S_t), W_{it}(S_t), \Lambda_{it}(S_t)$ satisfy the firms' Bellman equations;
- $d_i^*(S_t)$ solves the selected innovator's optimization problem;
- $C_{inmt}^*(S_t)$ determines the incumbent firm's capacity allocation across locations m and technology nodes n;
- $q_{inmt}^*(\mathbf{C}_{nm}, \mathbf{1}(\Psi_t < \psi))$ maximizes the firm's flow profit given the realization of trade disruption risks and capacity constraints $\mathbf{C}_{nm}$ across all firms and locations;
- $P_{nmt}(\mathbf{q}_{nmt}^*)$ ensures product market clearing.

Backward Induction

- Assume the terminal values associated with a firm's states and the corresponding industry states $\Lambda_{iT}(S_T)$
- At $T-1$, the picked innovator makes the dynamic decision to maximize

$$\max_{d \geq 0} \left\{ -c_{i,d}(S_{T-1})d + \beta \left[\begin{array}{c} \rho(d)[\Lambda_{iT}(S_T \mid S_{T-1}, a_{i,T-1} = 1) \\ +1(\bar{n}_T > \bar{n}_{T-1})\pi_{i,T-1}^{n=2}(S_{T-1})/(1-\beta)] \\ +(1-\rho(d))\Lambda_{iT}(S_T \mid S_{T-1}, a_{i,T-1} = 0) \end{array} \right] \right\}$$

- Solve this iteratively until the first period

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Additional Material

Two-Firm Illustration

Two-Firm Model Setup

Goals

- Understand firms' R&D patterns considering their technology status and response to subsidies
- Examine how the effectiveness of subsidies in fostering technology leadership is affected by firms' relative technology status

Setup

- No trade disruption risk
- Consider 2 firms subject to different investment subsidy rate τ
- Only the leading firm makes a positive profit in monopoly markets

Optimal R&D Investment Pattern

R&D Effort by Firm i
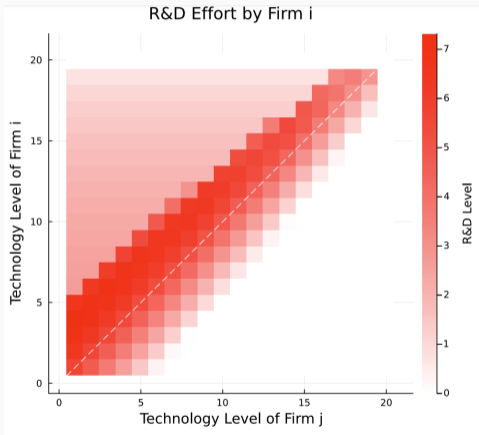
- Highest innovation when neck-and-neck
- Substantially lagging firms lose incentive to innovate
  - No leapfrogging
  - R&D must be a multi-period effort to catch up

Effects of Subsidies to *i* on R&D Investment - Subsidized Firm

Changes in R&D Effort by Firm i
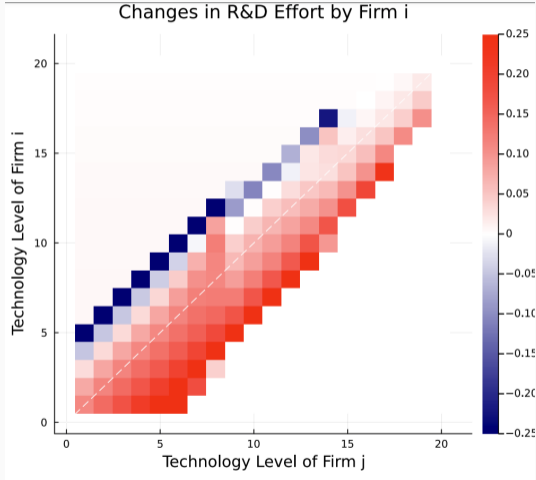
- No response when technology gap is too large
- Increase R&D in most cases as subsidies cover part of the cost
- Reduce R&D when leading in certain regions as R&D subsidy to leading firm further deters laggards

Effects of Subsidies to i on R&D Investment - Rival

Changes in R&D Effort by Firm j
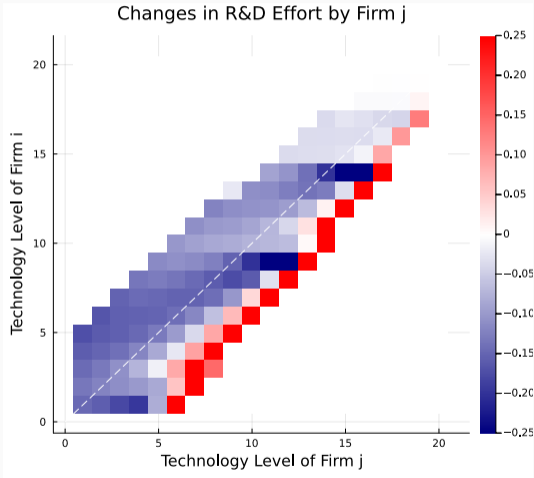
- No response when technology gap is too large
- Cut R&D when the subsidized firm leads or closely trails
- Rise R&D to prevent the subsidized firm from catching up when has a significant technological lead

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Technology Upgrading Dynamics

Same Initial Technology Level

- No Subsidy - Domestic Firm
- No Subsidy - Rival
- With Subsidies - Domestic Firm
- With Subsidies - Rival

Rival 2 Generations Ahead

Rival 4 Generations Ahead

Average Technology Level

Time

Back
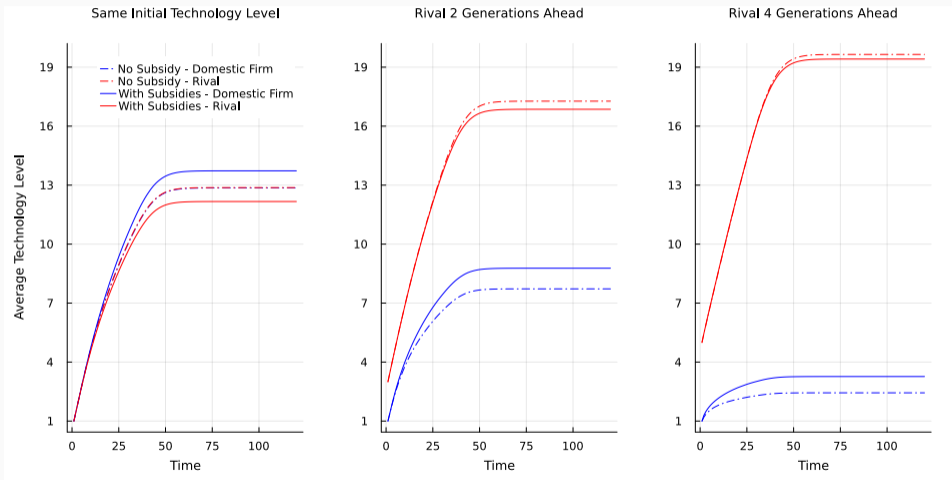
Timing's Influence on Industrial Policy Success

Subsidies in Period 1-20

Subsidies in Period 21-40

Subsidies in Period 41-60

No Subsidy - Domestic Firm
No Subsidy - Rival
With Subsidies - Domestic Firm
With Subsidies - Rival

Average Technology Level

Time

Back
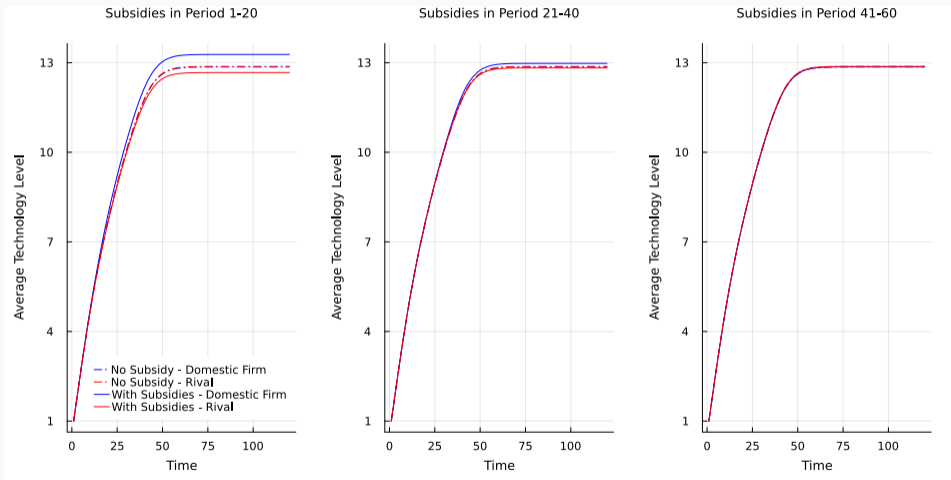
Data

- Pure Play Foundry Market Tracker from Omdia
  - Quarterly data from 2003Q1 to 2023Q3
  - Capacity, utilization, shipment, and revenue by firm and technology node
  - Focus on pure-play foundries, limited information on Samsung foundry

- 300mm Fab Outlook to 2026 from SEMI
  - Quarterly data from 2015Q1 to 2026Q4 (including prediction)
  - Firm, location, capacity, technology node, construction and equipment costs for each 300mm fab production line
  - Include IDMs like Intel and Samsung

- Other complementary data
  - Firm quarterly reports: revenue, COGS, and R&D costs
  - Industry analysis data from: IC Knowledge, BCG and SIA
  - Downstream shipment data

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Calibrated Parameters

Assume no trade disruption risk during the sample period

Calibrated Parameters

Parameter	Meaning	Value	Source
β	Discount factor	$0.9^{1/4}$	Quarterly rate
$\bar{N}$	Technology limit	16	ASML Roadmap
T	Final period	2059Q4	Sensitivity analysis (2045Q4)
ψ	Trade disruption risk	$[0, 1]$	Set as 0 in calibration
δ	Foreign cost shifter	$[1, 2]$	Only relevant in counterfactual

Age Effects on Demand

Demand Shift from Node Age

Quarters Since Node Introduction

95% Confidence Interval — Coefficient

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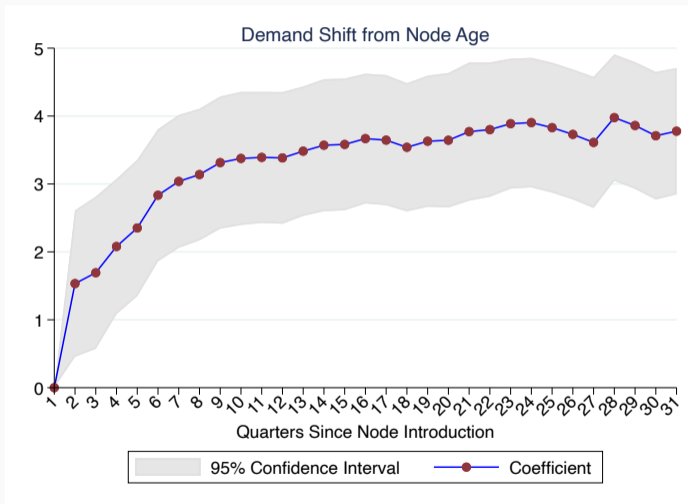
Parameterization, Calibration, and Estimation Results

Parameter	Functional Form	Value	Source
Discount factor		$\beta = 0.9^{1/4}$	Quarterly rate
Technology limit		$\bar{N} = 16$	Sensitivity analysis (11)
Final period		$T = 2059Q4$	Sensitivity analysis (2045Q4)
Trade disruption risk		$\psi \in [0, 1]$	Set as 0 in calibration
Foreign cost shifter		$\delta \in [1, 2]$	Only relevant in counterfactual
Market Share		$M_{US} = 25\%, M_{CN} = 22\%$	Downstream demand &
		$M_{ROW} = 53\%$	Estimated demand shifter coefficient
Firm-level productivity	ν_i	$\nu_{TSMC} = 1, \nu_{others} = 1/1.57$	Firm capacity share
Capacity unit cost	$\frac{w_{0,l}}{\nu_i}(1+g^w)^n(1-s_l)$	$w_{0,US} = 1, w_{0,CN} = w_{0,RoW} = 0.925$	BCG and SIA report
		$g^w = 25.8\%$	Unit investment cost growth
R&D unit cost	$c_0(1+g^c)^n \gamma^{1(\Delta n_R > 0)}$	$c_0/10^6 = 3.2\ [1.5, 3.5]$	MLE
		$g^c = 28.8\%$	TSMC R&D cost trend
		$\gamma = 22\%\ [7\%, 92\%]$	MLE

Moore's Law   Market Size Definition   Trends in Equipment and R&D Costs   Firm R&D Cost Comparison   Back

Moore's Law Extrapolation

TSMC's Trajectory (Moore's Law)

Back
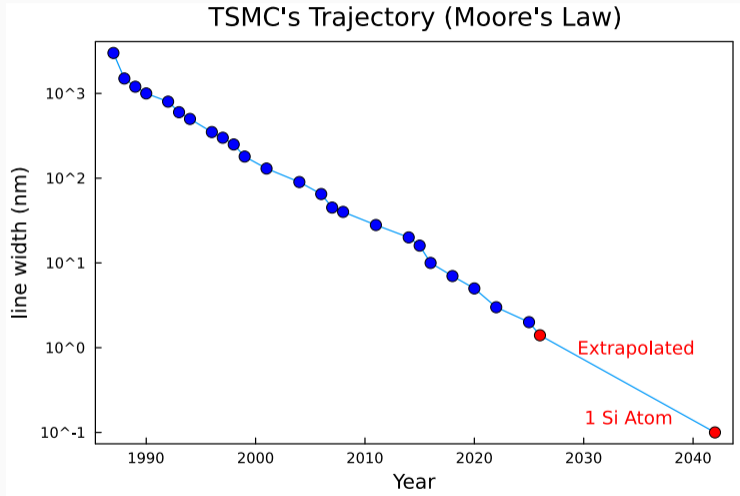
Trends in Equipment and R&D Costs
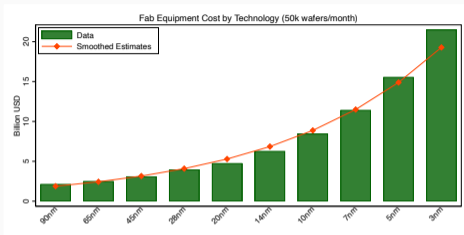
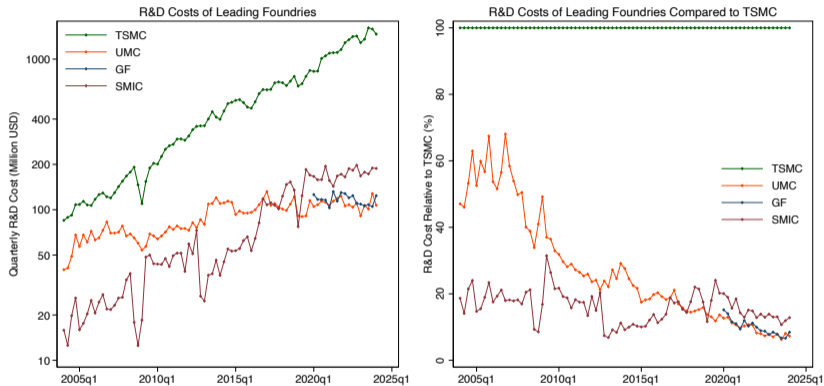**Source:** SMIC prospectus and author's calculation
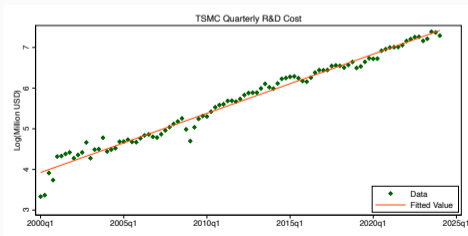
Source: TSMC's quarterly reports and author's calculation

- Both investment costs and R&D expenditures increases exponentially with advancing technology nodes
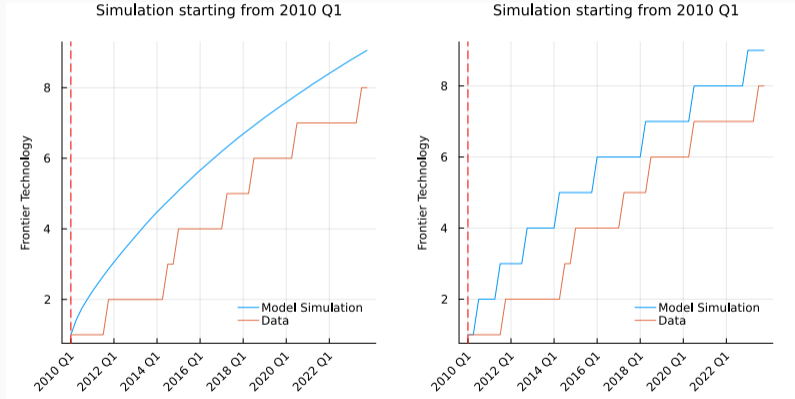
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R&D Costs of Leading Foundries

Source: Firms' quarterly reports and author's calculation

Market Size

- Define market size based on downstream demand for smartphones, tablets, and PCs
- From the demand estimation: $N_m \propto Q_{PC,m}^{\alpha_D^{PC}} Q_{mobile,m}^{\alpha_D^{mobile}}$
- Estimated market size shares: US 25.2%, CN 22.2%, RoW 52.6%

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- Frontier technology trajectory: model vs. data

Back

Model Fit - Frontier technology trajectory

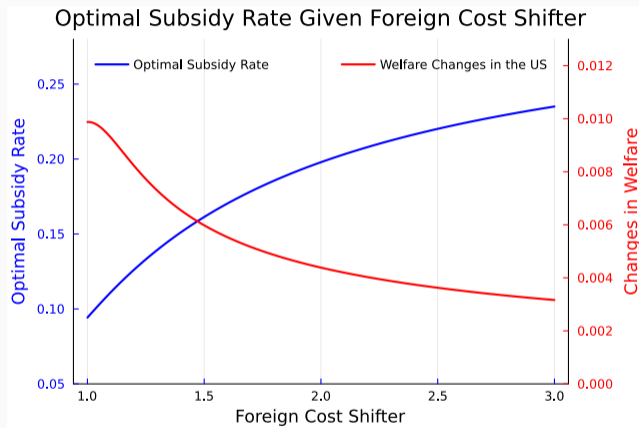- Frontier technology trajectory: model vs. data

Model Fit - Frontier technology trajectory
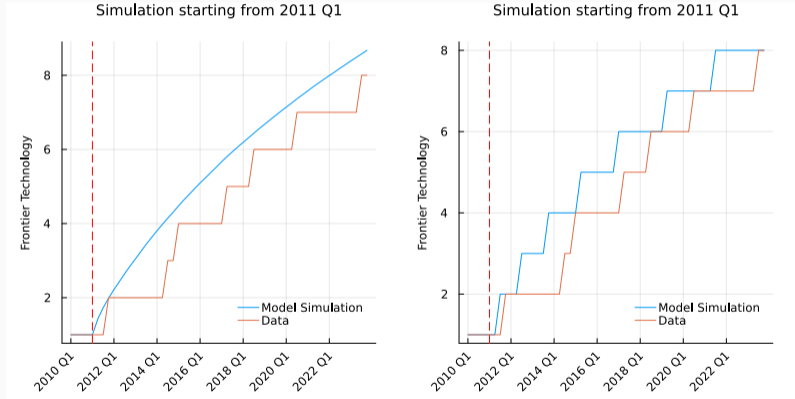
- Frontier technology trajectory: model vs. data
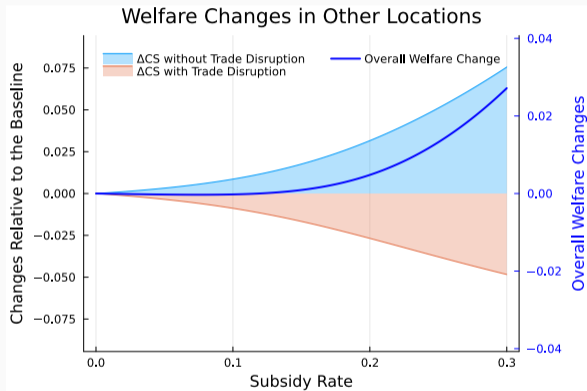

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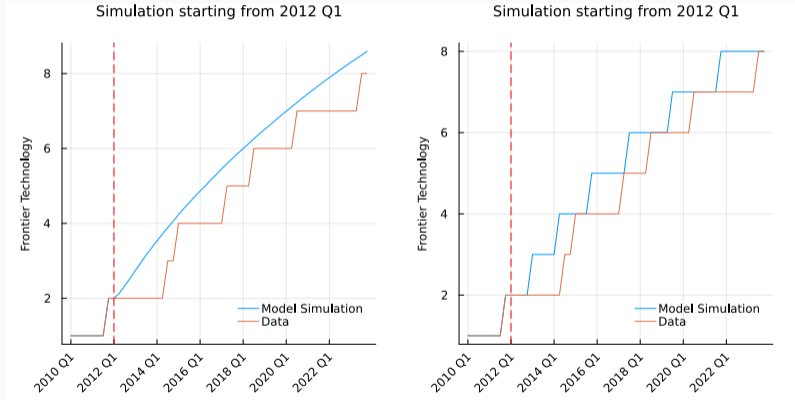
Static Gains in the US: Monopoly Case
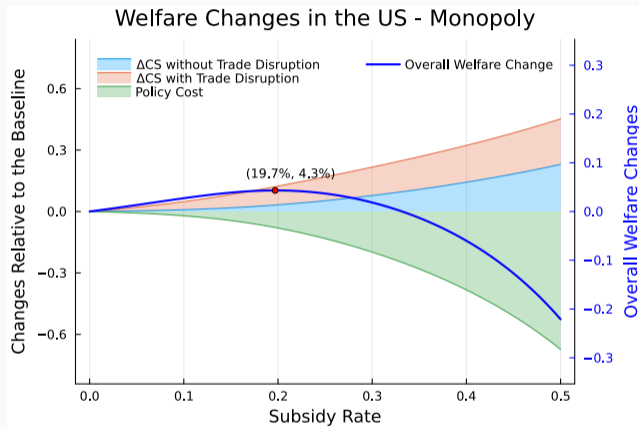
Monopoly case: $\delta = 1.0, \psi = 0.2$

Setting: 2 incumbents, $\psi = 0.2$
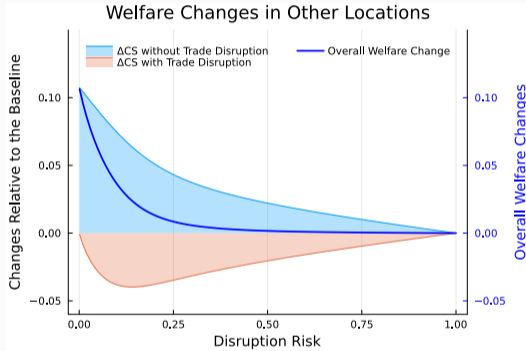
Back

Static Gains in Other Locations

Welfare Changes in Other Locations

Baseline case: 2 incumbents, $\delta = 1.0, \psi = 0.2$

- US subsidies shift capacity to the US, raising prices elsewhere during trade disruptions but lowering global prices without disruption
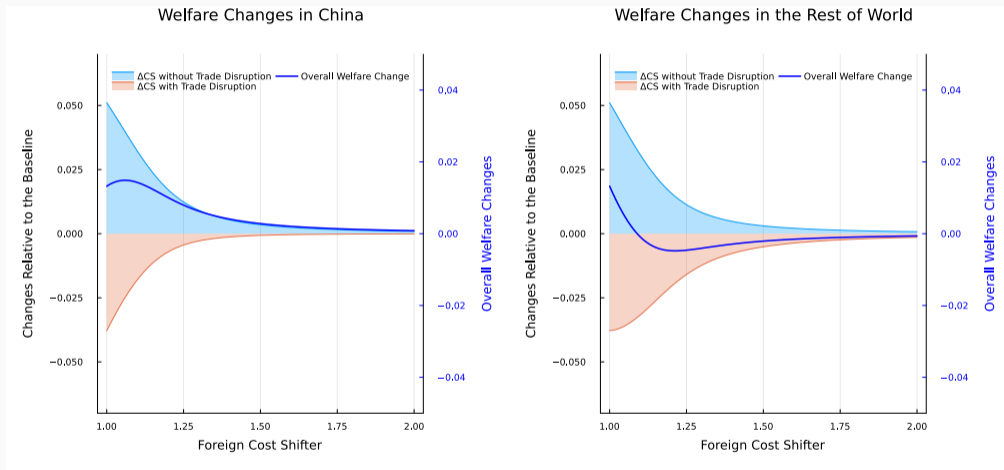
Static Gains in Other Locations

Welfare Changes in Other Locations

Setting: 2 incumbents, $\delta = 1.0$, $s_{US} = 25\%$

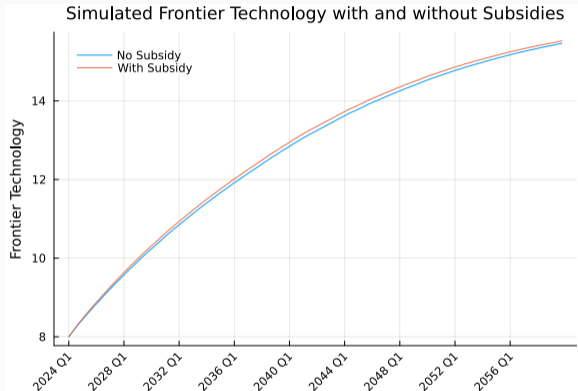Foreign Cost Shifter δ Back

- US subsidies shift capacity to the US, raising prices elsewhere during trade disruptions but lowering global prices without disruption

- Other locations benefit less from US subsidies as trade disruption risk rises

Static Gains in Other Locations: The Role of δ

Welfare Changes in China

Welfare Changes in the Rest of World

Setting: 2 incumbents, $\psi = 0.2$, $s_{US} = 25\%$

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Gains from Faster Technology Upgrades

Simulated Frontier Technology with and without Subsidies

Baseline case: $\delta = 1.0, \psi = 0.2, s_{US} = 17\%$

Dynamic Gains in the US: No Disruption Risk

Welfare Changes in the US: No Disruption Risk

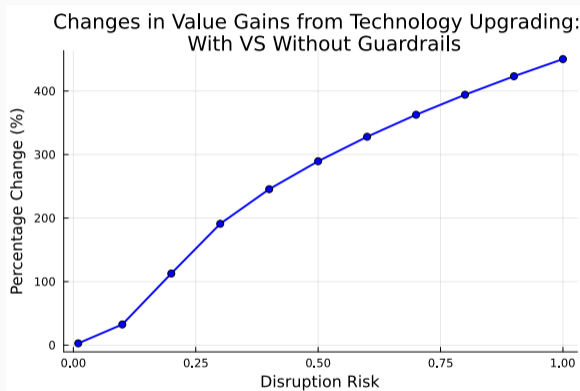**Setting:** $\delta = 1.0, \psi = 0.0$

Back
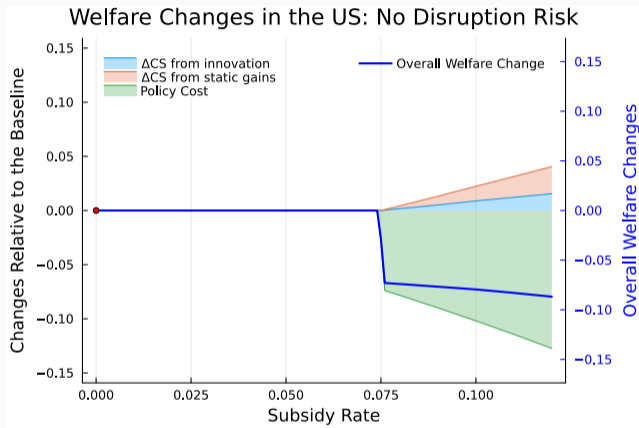
Guardrail Restrictions

Optimal R&D effort

$$d^*(S_t) = \max\{0, \sqrt{\beta \frac{\Lambda^{gap}(S_t)}{c_d(S_t)}} - 1\}$$

- $\Lambda_{gap}(S_t)$: expected value gain from technology upgrading
    - Secure the domestic market demand for CN firms during trade disruptions
    - $\Delta\Lambda^{gap}(S_t) \uparrow$ as disruption risks $\psi \uparrow$
- $c_d(S_t)$: unit cost of R&D - $c_0(1 + g^c)^n \gamma^{1(\Delta n_{it} > 0)}$
    - Higher unit cost when CN firms are followers
    - $\gamma \to \alpha\gamma$ with the spillover reduction factor $\alpha \geq 1$

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Minimum α for Effective Guardrails

Changes in Value Gains from Technology Upgrading: With VS Without Guardrails

Note: Changes in Λ_{gap} for SMIC in 2024Q2 with and without guardrails, $s_{US} = 25\%, \delta = 1.0$

- To curb CN firm's innovation: ↑ disruption risks $\implies$ ↑ spillover blocking

- Export controls and the Huawei ban ↑ disruption risks in CN

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