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Manufacturing flexibility to mitigate vulnerability to PEV critical mineral supply-chain disruptions

JP Pieper, Jason O'Connor, Valerie Karplus, Kate S. Whitefoot

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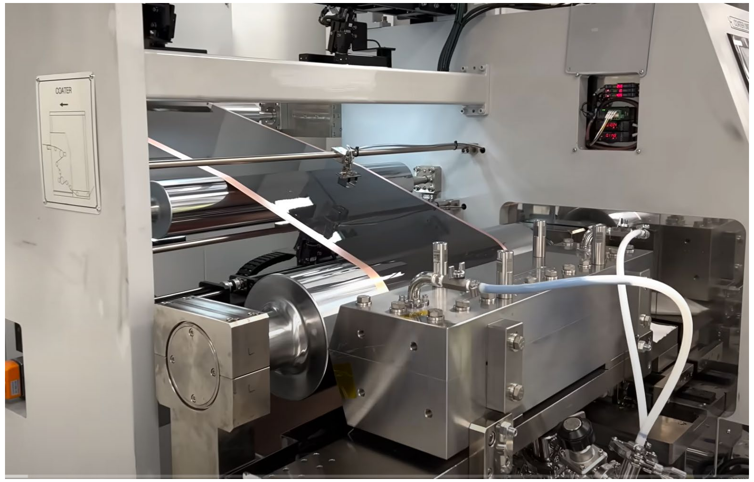
Engineering & Public Policy, Mechanical Engineering PhD Student

Outline

- Motivation and Research Question
- Implementation of manufacturing flexibility for batteries and PEVs
- Economic value of manufacturing flexibility
- Discussion and Future work



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Photos sources from ONE pilot plant from Youtube video. They depict slurry mixers, slot-die coaters, and cell stacking of prismatic cells

Motivation: Critical mineral use and global vehicle electrification

Automakers stating to electrify 25%-70% of fleets by 2030-2035 using electric vehicles[1] (EVs) BMW, GM, JLR, Hyundai, KIA, Mazda, Mercedes, Mitsubishi, Subaru, Toyota, VWA, Volvo, etc.

Automakers make large, often irreversible, investments now under future uncertainty.

Cathode active material (CAM) inputs **(e.g., cobalt, lithium, nickel)**, have supply chains that are **geographically concentrated and face vulnerabilities**. (Olivetti et al., 2017; Cheng et al., 2024)

Increased adoption of BEVs leads to higher firm exposure to critical mineral disruption risks.

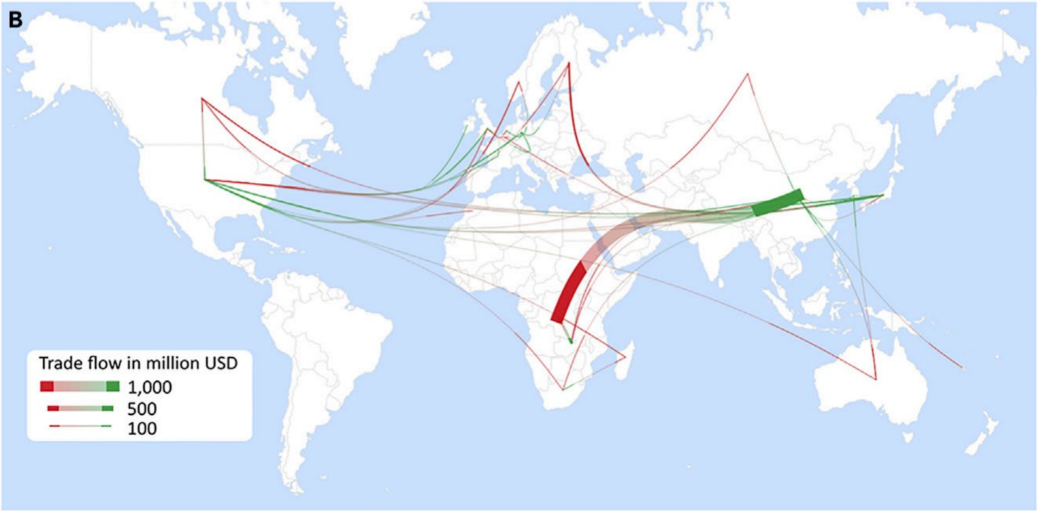

Figure 1. Global cobalt trade flows from 2015 trade where red indicates origin and green indicates destination. Sourced from (Olivetti et al., 2017).

[1]Electric vehicles refer to vehicles containing an electric powertrain component. Battery electric vehicles (BEV) use electricity as 100% fuel source. Plug-in electric vehicles (PHEV) have both electric and conventional powertrains.

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Future U.S. automotive market is expected to have large exposure to cobalt and lithium volatility

Based on automaker stated offerings, we estimate a future 2030 market with 75% of BEVs using NMC_{811}:

- Based on consumer preference for high-range, high power [1]
- The U.S. has low cobalt refining capabilities
- Given plausible future cobalt disruptions [2], we estimate producer and consumer surplus losses of **$4B** and **$1.4B**, respectively
- Current mitigation measures include major PEV investment scale backs

The U.S. has potential for large-scale LFP upstream production:

- Domestic lithium investments: Thacker Pass, Smackover, Rhyolite
- Could LFP be a viable substitute within the transportation energy transition?

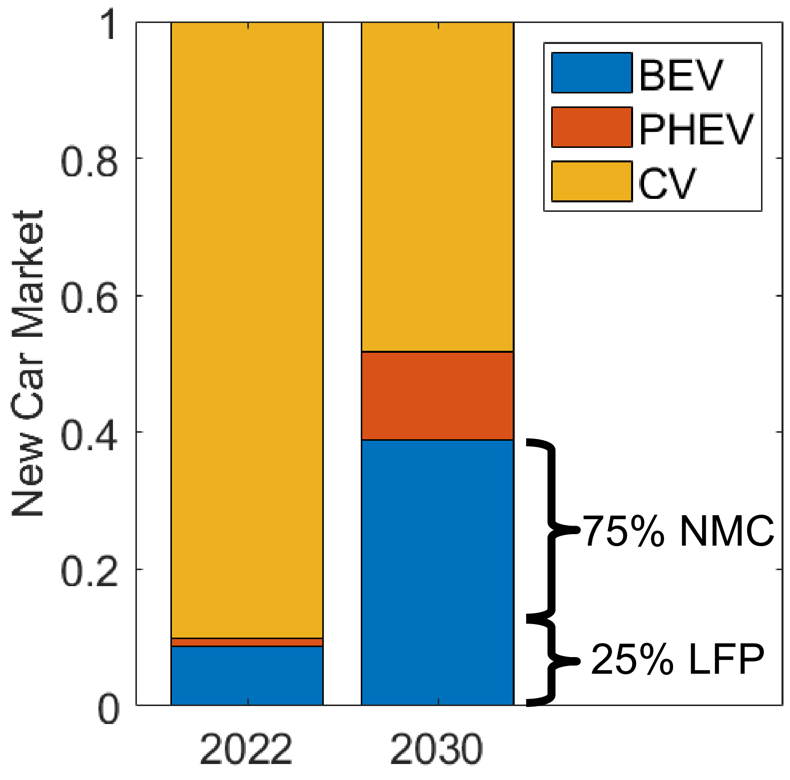

Figure 2. 2022 Market data on firm offerings and a 2030 estimated future market based on offerings and stated firm future offerings.

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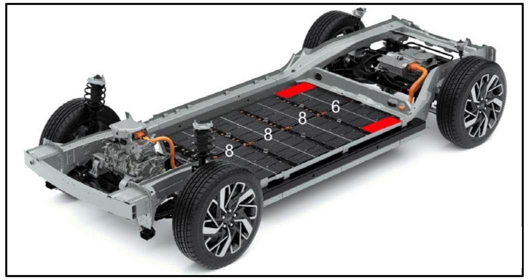
1) Forsythe et al., 2023; 2) Olivetti et al., 2024 (NNCTA);

CAM choice leads to imperfect substitutes and changes in vehicle performance

$LiNi_8Mn_1Co_1O_2$ (NMC_{811})

↑ Power density



↑ Capacity

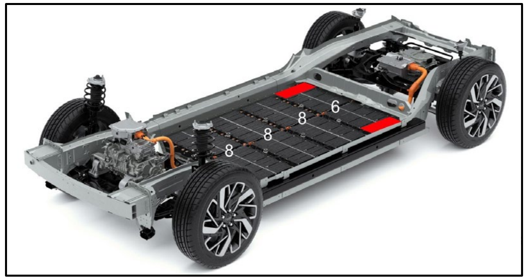
↑ Thermal management

↑ Range ↑ Cost

Equivalent volume

$LiFePO_4$ (LFP)

↓ Power density



↓ Capacity

↓ Thermal management

↓ Range ↓ Cost

Image source: Hyundai IONIQ Forum; Wikipedia.

Research Question: **Under what conditions should automakers and battery manufacturers jointly invest in the ability to switch CAM production to mitigate critical mineral supply chain disruptions?**

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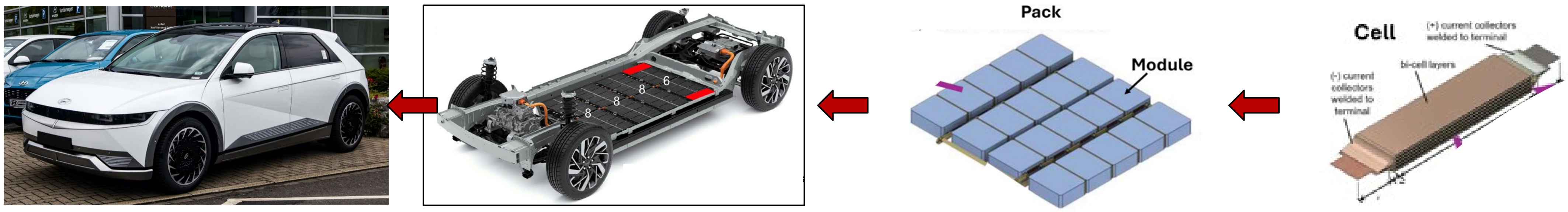
Objectives:

- Examine a feasible design and evaluate tradeoffs of switching CAM from NMC_{811} to LFP on battery production lines and in electric vehicle design (LFP prequalification).
- Model market implications LFP prequalification considering cobalt supply disruption risk, vehicle performance & cost tradeoffs, and competitive firm behavior.



NMC_{811} or LFP

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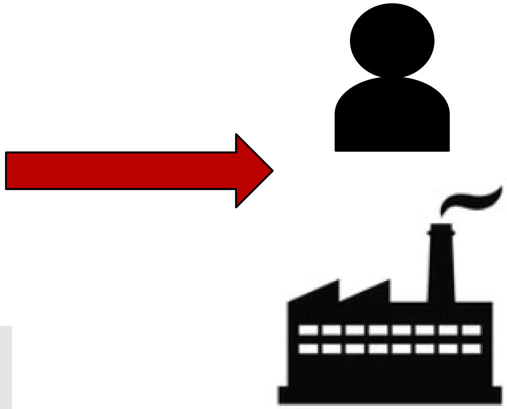
NMC_{811} or LFP



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Literature Review

Battery cost models[1,2,3,4,5] exist without incorporation of market responses to design tradeoffs

Flexible battery and automotive manufacturing literature [6,7] alludes to value, but lacks a feasibility analysis incorporating product and process redesign.

There exist product design [8,9] and real option [10,11] frameworks to identify market responses to design changes under uncertainty while incorporating market equilibrium[12,13] and consumer demand models[14,15,16].

Our framework estimates the value of feasible battery and PEV redesigns under disruption uncertainty and market systems.

1. (Knehr et al., 2022); **2.** (Wentker et al., 2017); **3.** (Ciez & Whitacre, 2017) ; **4.** (Sakti et al., 2015); **5.** (Mauler et al., 2021; **6.** (Kampker et al., 2023); **7.** (Nelson et al., 2015); **8.** (Hazelrigg, 1998); **9.** (Donndelinger & Fergeson, 2020) ; **10.** (de Neufville et al., 2006); **11.** (Kang et al., 2018); **12.** (Olivetti & Whitefoot et al., 2024); **13.** (Shiau & Michalek et al., 2007); **14.** (Vicente et al., 2025); **15.** (Forsythe et al., 2023); **16.** (Train, 2003)

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Methodology – Valuing CAM flexibility

Identify battery & PEV product and process changes

- Create a battery design model to identify design changes [1,2]

Real options framework:

- Upfront investment creates the right, not obligation to switch CAMs later

Firms maximize expected net present value under:

- Cobalt disruption parameters (probability and magnitude)
- Binary flexibility investment
- Discrete CAM choice
- Market equilibrium
- Continuous pricing

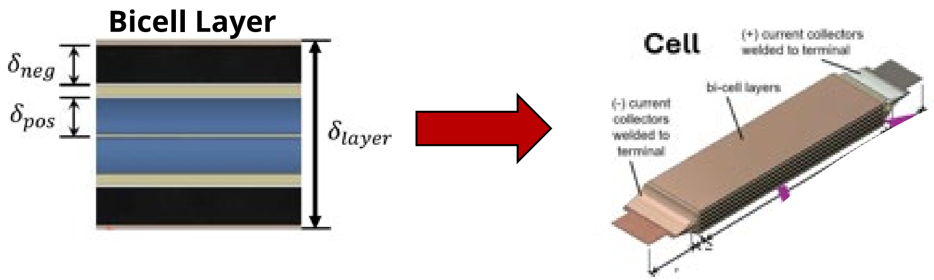
(Binary flexibility investment, Discrete CAM choice: Binary-NLP)

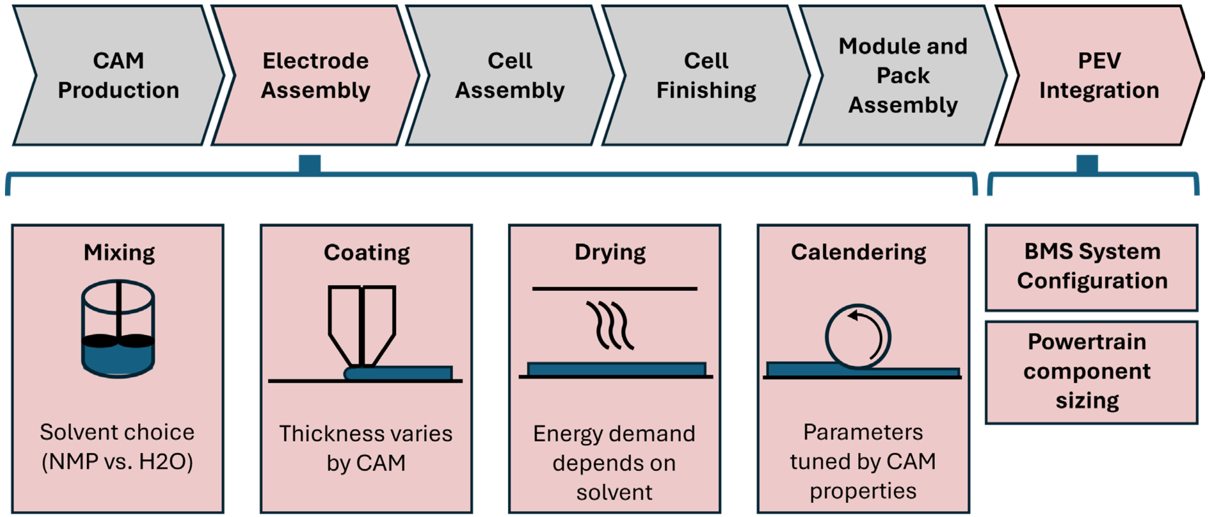
(Market equilibrium, Continuous pricing: Estimate Nash using SIO [3])

Demand estimated using a mixed-logit vehicle choice model [4]

[1] Knehr et al., 2023; [2] Wentker et al., 2019; [3] Shiau & Michalek, 2007; [4] Forsythe et al., 2023

Technical Design Considerations of Flexible Battery Cell Production (NMC to LFP)





Considering cell interior dimensions, LFP and NMC cells have varying electrode thickness when optimizing for energy [1,2]

NMC and LFP cell production steps share most capital equipment*, with major differences within intermediate inputs and process parameters [3,4,5,6,7,8]

When changing the battery pack CAM, one must consider,

- Changes in pack nominal voltage [9,10]
- BMS changes [11]

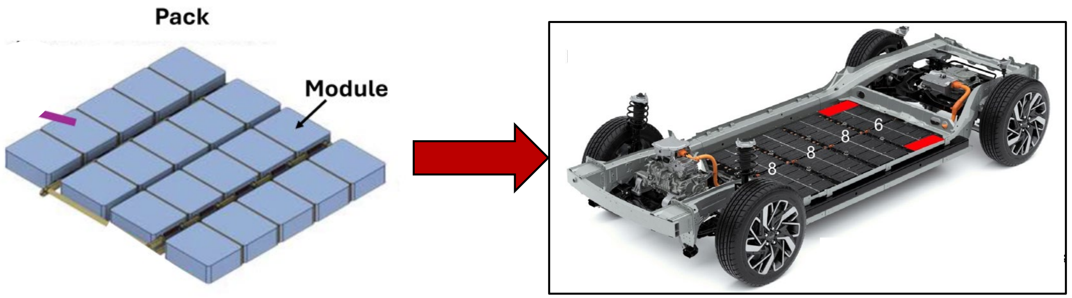
To use different CAM in production line, producers **prequalify** new material:

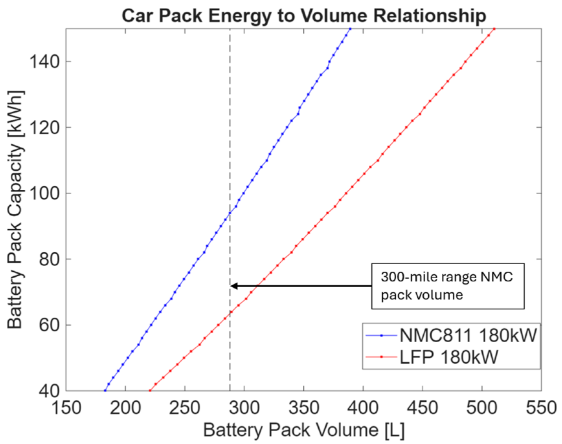
- Lab tests and simulations for optimal design: $100,000 †
- Qualify cell on production line: 7-14 days †

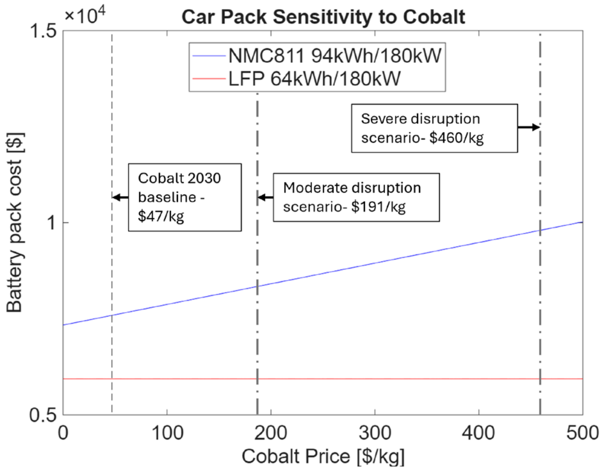
† From expert interviews with battery manufacturing experts conducted May 2024-January 2025

1. (Li et al., 2022); 2. (Link et al., 2023); 3. (Kampker et al., 2023); 4. (Bryntesen et al., 2021); 5. (Duquesnoy et al., 2024); 6. (Kays et al., 2023); 7. (Zhang et al., 2021); 8. (Kwade et al., 2018); 9. (Li et al., 2021); 10. (GVM Motors); 11. (Tran et al., 2021)

Technical Design Considerations of Flexible PEV Production (NMC to LFP)







To minimize PEV redesign for short-run pack change, we constrain pack, module, and cell volume, series/parallel configuration.

We model internal cell changes, such as electrode thickness and number of bi-cell layers

We estimate volumetrically equivalent designs for 300-mile range, 2030 PEV cars and SUVs using BatPaC (Knehr et al., 2023)

We model pack cost using BatPaC and use Cellest to model pack exposure to cobalt price (Knehr et al., 2023); (Wentker et al., 2017)

Table 1. Battery and electric vehicle characteristics for NMC811 and a volumetrically equivalent LFP for a projected 2030 300-mile range BEV separated by car and SUV. Note that battery pack cost assumes a baseline cobalt cost of $47/kg.

BEV Battery Characteristics	Car		SUV	
	NMC_{811}	LFP	NMC_{811}	LFP
Pack Total Capacity [kWh]	94	64	144	97
Rated Pack Power [kW]	180	180	220	220
Cell Format	Stiff pouch	Stiff pouch	Stiff pouch	Stiff pouch
Pack Volume [L]	288	288	378	378
Estimated AER [mi]	300	204	300	202
Cathode Thickness [μm]	155	165	155	165
Pack Cost [$]	7608	5971	10527	7930
Pack Cost [$/kWh]	81	93	73	81
CAM cost per pack [$]	2330	457	2996	700
CAM cost share of pack [%]	31%	8%	28%	9%
CAM material and preparation cost [$/kg]	18.42	8.35	18.42	8.35
CAM material and preparation cost [$/kWh]	24.78	16.52	24.79	16.52
CAM mass per pack [kg]	127	127	194	192
Slurry solvent choice	NMP	Water	NMP	Water

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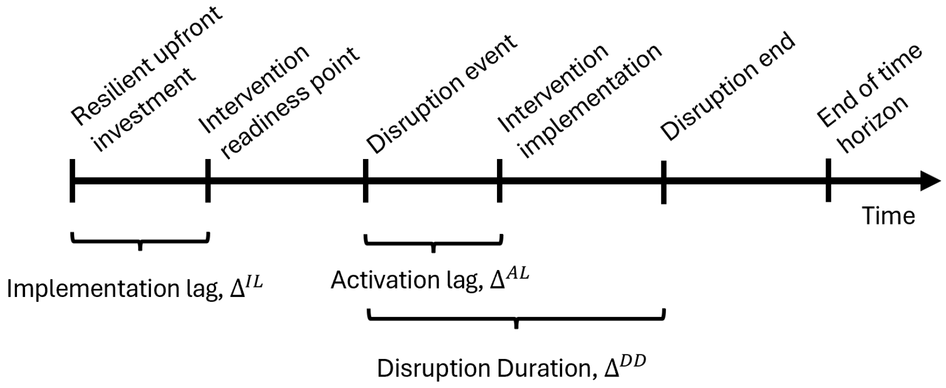
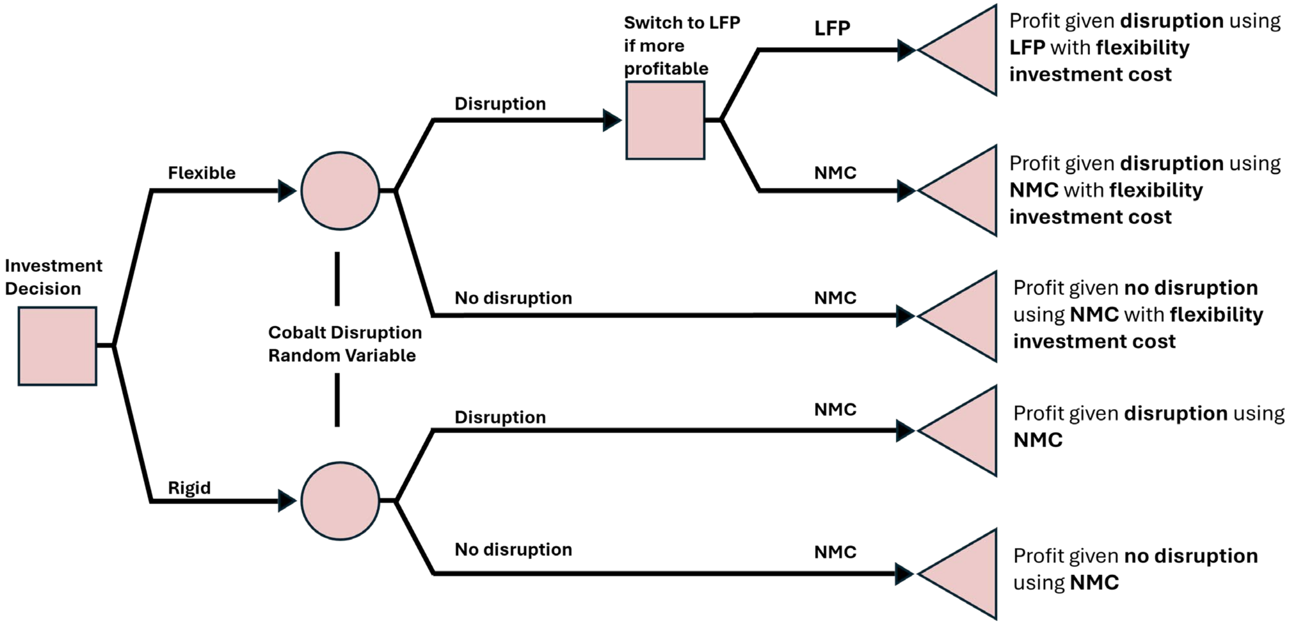
Embedding CAM flexibility within the initial design

We propose firms implement CAM flexibility within the initial vehicle design

- Invest in flexibility when there's no disruption
  - Assume 2-year LFP-supplier coordination
- Rapid change can be made given a disruption

Given a disruption event, firms then choose to switch CAM based on maximizing profits





Real options framework to assess expected value of flexibility

Expected value of flexibility(Hassan et al., 2005; deNeufville, 2006), E[VoF], for a firm:

$$E[VoF|c^{Co}, P]_f = E[NPV^{FLEX}|c^{Co}, P]_f - E[NPV^{RIGID}|c^{Co}, P]_f$$

Magnitude and Probability of Cobalt Disruption

Table. Cobalt supply disruptions from (Olivetti & Whitefoot et al. 2024)

Scenario Description	Quantity	Estimated Median Price (2023 USD)
Baseline scenario	302 kt	$47/kg
(S1) U.S. import restrictions due to human rights concerns reduce cobalt imports from artisanal mining by 14%	274 kt	$191/kg
(S2) Natural disasters in the DRC reduce global raw cobalt supply by 65 kt (25%)	258 kt	$460/kg

Firm Adoption (A) of CAM Flexibility

- **Single firm investment (first-mover):** Value Of Flexibility For Automakers Moving Before Competitors
- **Simultaneous investment by all firms:** Value Of Flexibility When All Automakers Can Switch Chemistries

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Expected Value of Flexibility for First-Mover Access

Example firm: Hyundai – Large, BEV-heavy firm with diversified CAM (NMC and LFP)

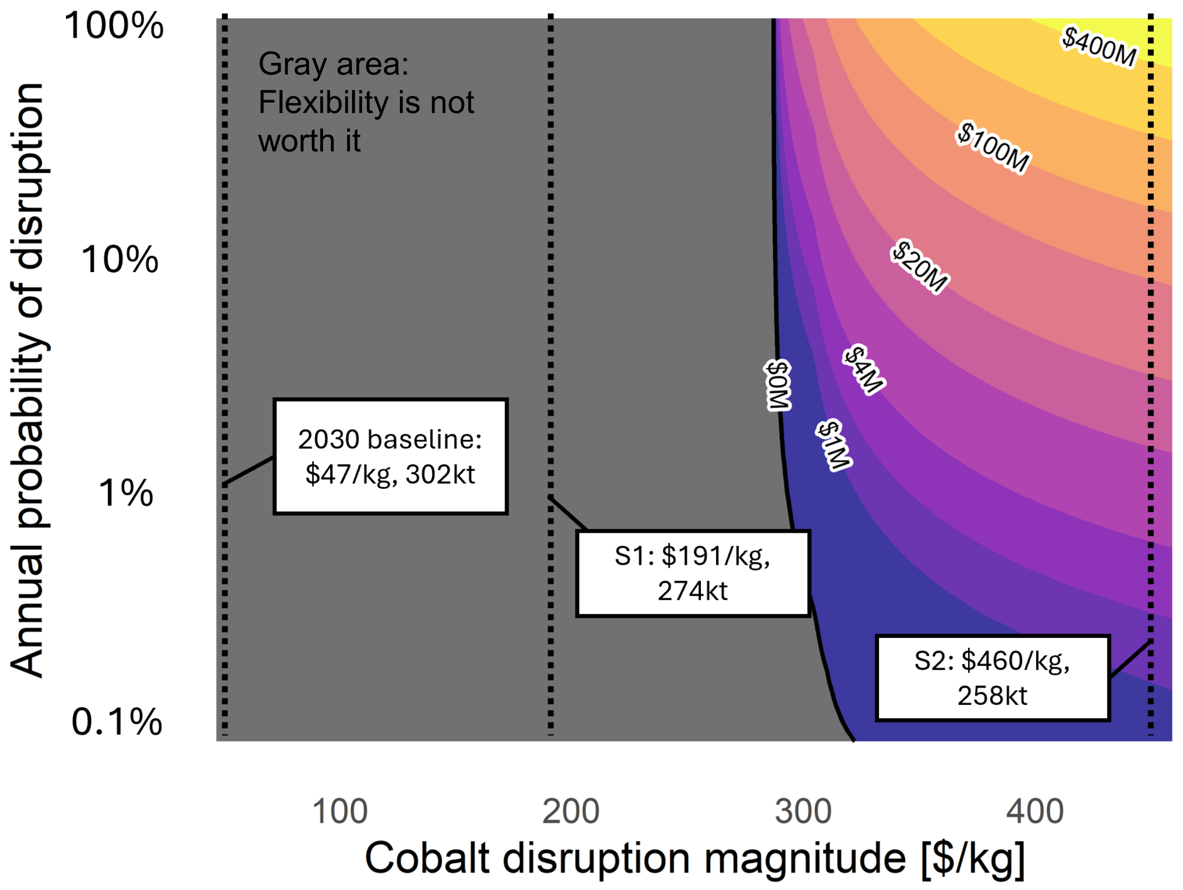

Figure 4. Expected value of flexibility for Hyundai (single representation) versus cobalt disruption price magnitude versus varying disruption probability. S1 and S2 represent the two disruption scenarios outlined within Tab. 2

We estimate the profit maximizing strategy and payoff for each firm given cobalt disruption characteristics

Plausible disruption scenarios [1]:

- S1: U.S. import restrictions due to human rights concerns in DRC – 14% U.S. supply restriction
- S2: Natural disaster in DRC hits top 3 mines – 25% U.S. supply restriction

In general, VoF is positive for disruptions over $300/kg at low probabilities (<0.01%)

We find no value for mana

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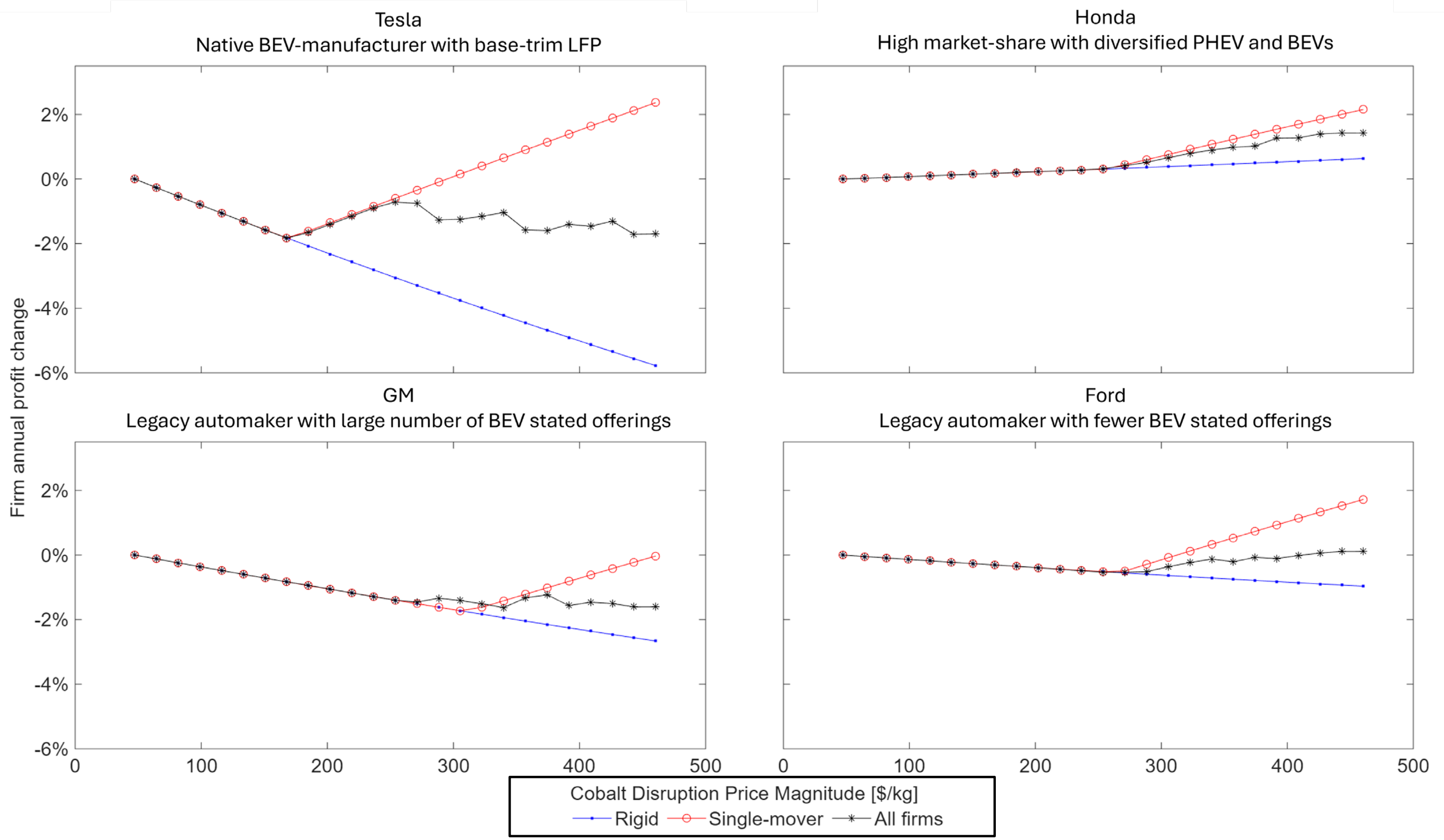
[1] Olivetti et al., 2023

Value of Flexibility given Market Access to Flexibility



Value of flexibility differs between firms based on:

- Firm size
- Cobalt exposure
  - Powertrain offerings
  - NMC/LFP baseline
- Single-firm/full-market flexibility

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Simultaneous Market Investment and Surplus Analysis

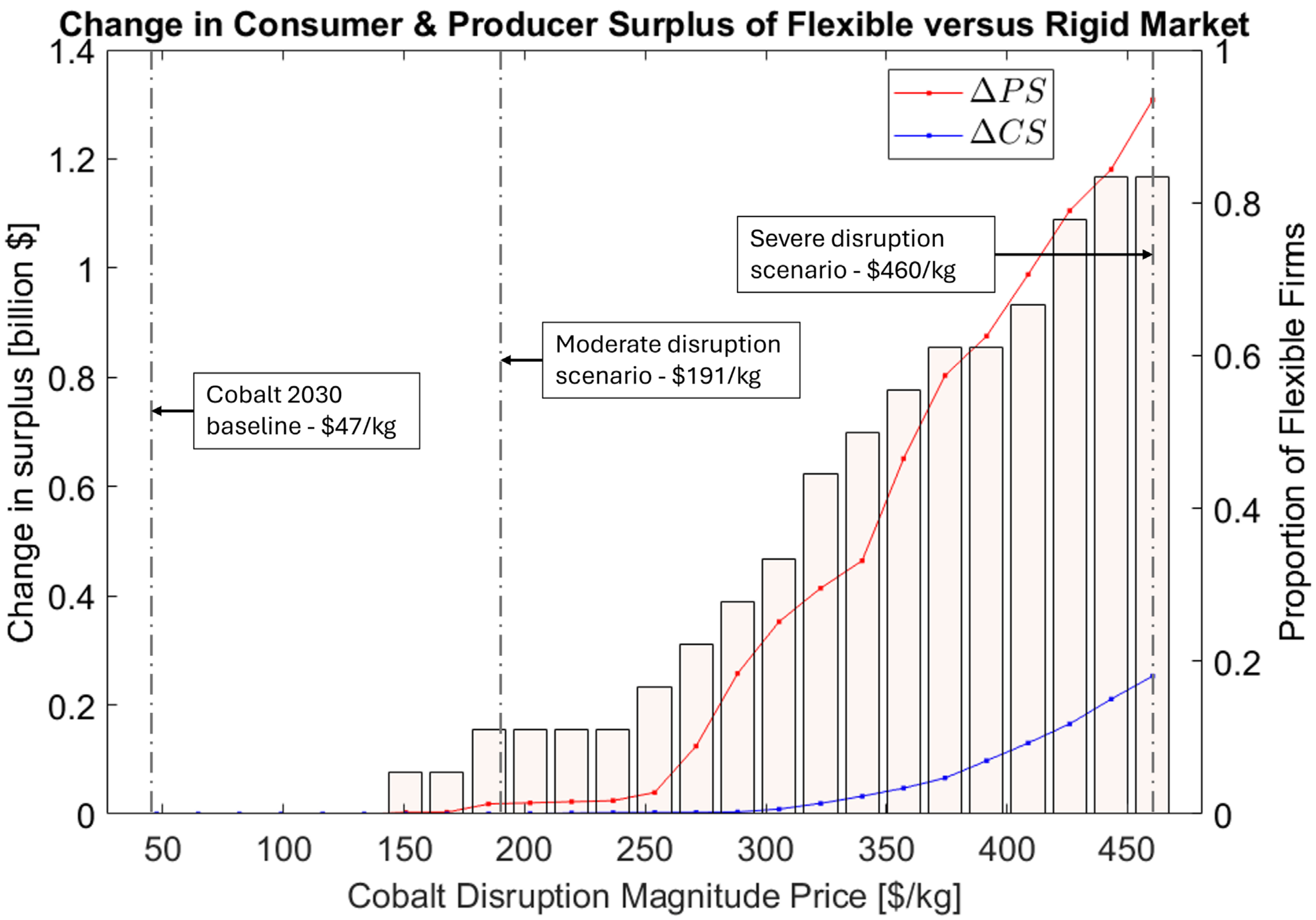

Figure 4. Change in producer and consumer surplus from a flexible market relative to a rigid one and proportion of firms simultaneously investing in flexibility for varying cobalt disruption price magnitudes. Note that the producer surplus curve is not smooth, due to the entry of firms with fixed capacity investing in CAM flexibility as cobalt disruption price magnitude increases

We estimate the profit maximizing strategy and payoff across the market given cobalt disruption characteristics

For severe disruptions, we find:

- In general, E[VoF] remains positive for firms
- Average vehicle price drops 2.7%
- Producer and consumer surplus increase by $1.3B and $250M, respectively

$$\Delta PS = \sum_{f\in F} \Pi_f^{FLEX}(c_t^{Co}) - \sum_{f\in F} \Pi_f^{RIGID}(c_t^{Co})$$

$$\Delta CS = \frac{m}{N}\left(\sum_{i}^{N} E\left(U_i^{FLEX}(c_t^{Co})\right) - \sum_{i}^{N} E\left(U_i^{RIGID}(c_t^{Co})\right)\right)$$

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Flexible U.S. BEV market decreases critical mineral exposure

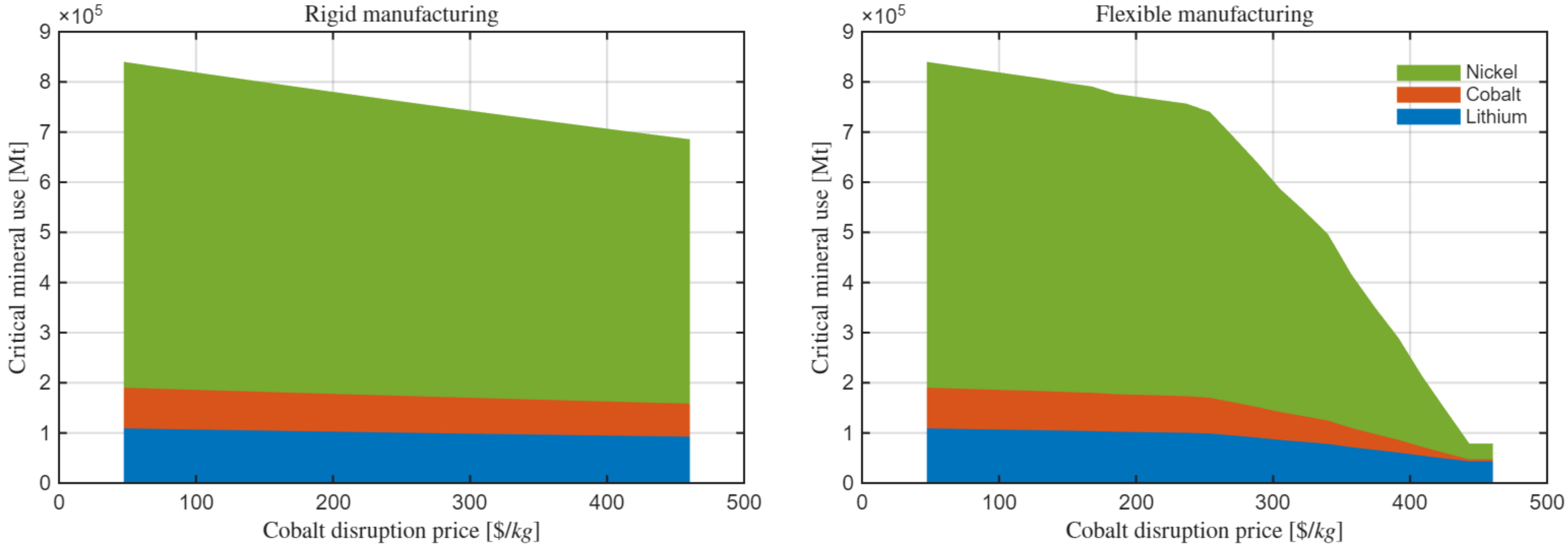

Figure. Annual U.S. automotive market critical mineral demand for rigid and flexible (i.e., full-market simultaneous investment) market competition scenarios for varying cobalt disruption price.

Discussion & Future Work

CAM flexibility includes technical feasibility and operational readiness:

- CAM flexibility requires firm operational knowledge through lab validation, process parameter identification, and PEV-interface compatibility

Economic value depends on disruption timing, scale, and exposure:

- Large, BEV-heavy firms capture most value as a strategic hedge, whereas diversified or PHEV-heavy firms see less value

Policy implications and U.S. domestic critical-minerals:

- CAM flexibility provides a rapid pathway to access emerging domestic LFP suppliers, mitigating disruption impacts on consumers and producers

Future work:

- What are different flexible manufacturing investments that firms can make given disruption uncertainty and how do they compare? (e.g., stockpiling, modular design, system-level flexibility, etc.)

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Thank you!

Contact: jppieper@andrew.cmu.edu

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