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Customer:
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Program Executive Office for Ground Combat Systems (PEO GCS)

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Implementing the CPAT Mixed-Integer Fleet Modernization Model

Deriving a computational model from business needs

U.S. DEPARTMENT OF ENERGY | NNSA

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GCS Business Needs

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- The U.S. army has a large fleet of ground combat vehicles that must be maintained, upgraded, and replaced over time
- The U.S. Army's Program Executive Office for Ground Combat Systems (PEO GCS) is responsible for developing investment plans and fleet transformation schedules
- There must be an analytic basis for ground combat system portfolio planning decisions

GCS Business Needs

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- How should the army's fleet of GCS vehicles evolve over the next two decades?
- Considerations
  - Budget Projections
  - Vehicle upgrade and purchase options
  - Vehicle performance characteristics
  - Production constraints
  - Research Investments

CPAT's Contribution to the Analytical Basis

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How should the army's fleet of GCS vehicles evolve over the coming years?

What is the best fleet we can put into service?

What is the maximum achievable sum of yearly performance of vehicles in service throughout the study horizon?

This is not a pipe.

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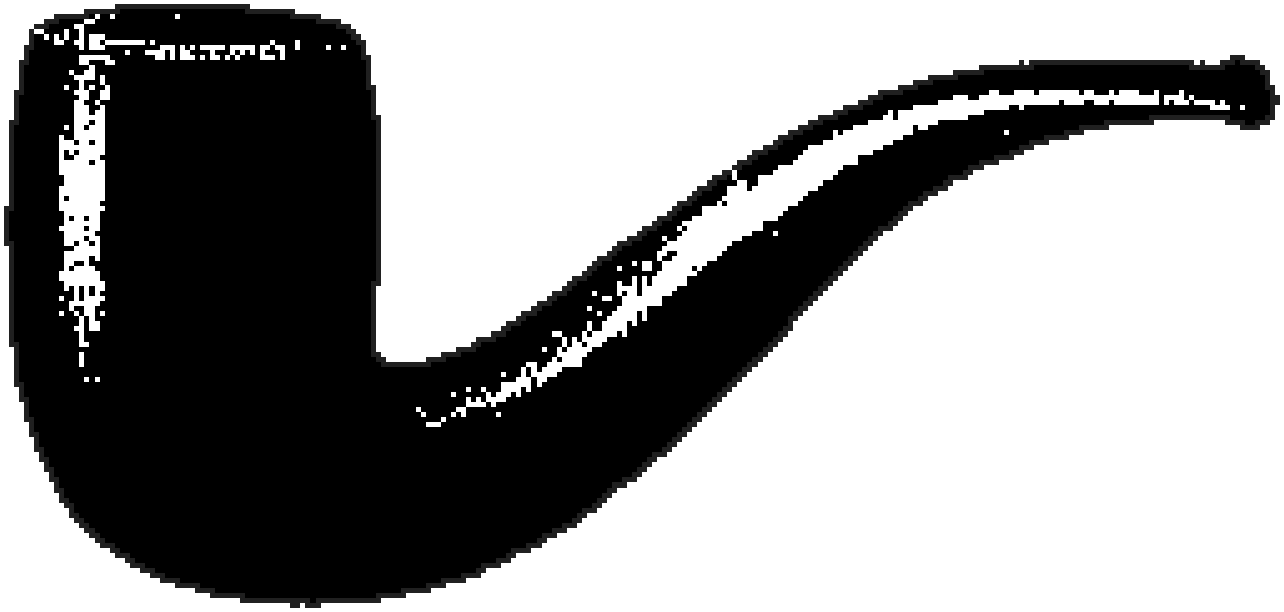
The Treachery of Images - René Magritte, 1929
Los Angeles County Museum of Art

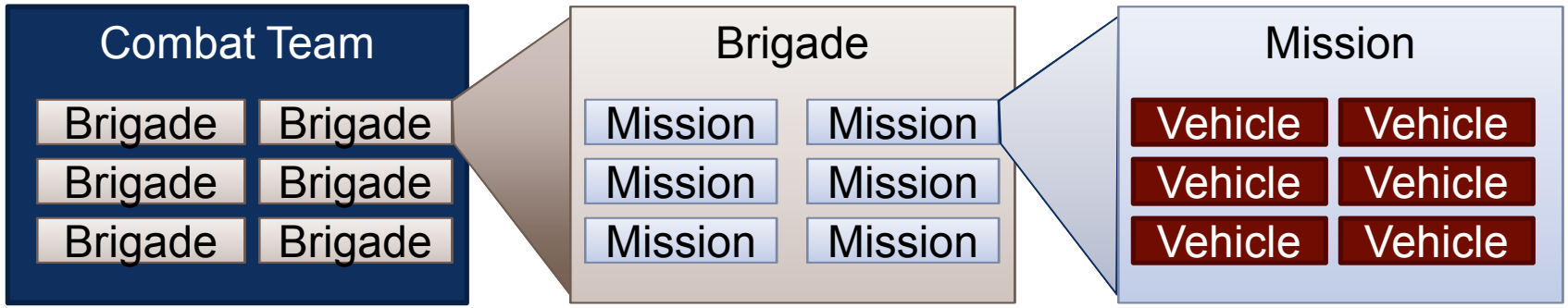
This is not a pipe

- Low-Res Version



Ceci n'est pas une pipe.

CPAT Fleet Structure

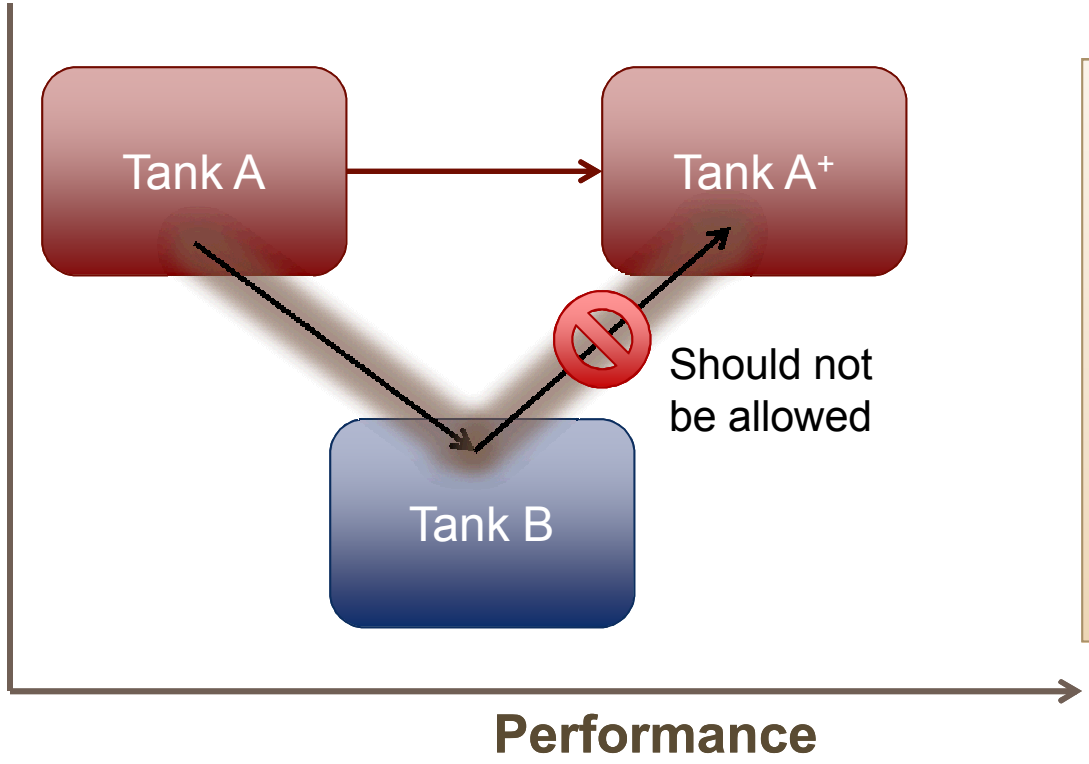


- Structure
  - Combat teams composed of brigades
  - Brigades fulfill multiple missions
  - A pre-defined number of vehicles are dedicated to each mission
- Similarity
  - All brigades in a combat team have the same missions and vehicle requirements
  - All vehicles serving the same mission in the same brigade must be the same vehicle type

CPAT Model

- Input parameters
  - $\alpha_{i,m}$=Performance of vehicle *i* serving mission *m*
  - Q_m=Number of vehicles required for mission m
- Decision Variables
  - $BrigInService_{i,m,t}$=Number of brigades using vehicle type *i* for mission *m* in year *t*
- *Objective Function:* Maximize cumulative fleet performance
  - $$\max \sum_{i,m,t} BrigInService_{i,m,t} Q_m \alpha_{i,m}$$

Issue: Unrealistic Upgrade Paths



- Some modernization choices improve performance, but should never occur
- Also, costs depend on what you are upgrading from

Transition-Based Model

- New Input Parameters
  - $IsValidTx_{i,j,m}$ = Boolean indicating whether vehicle *i* is allowed to be replaced by vehicle *j* in mission *m*
  - Cost changed from per-vehicle ($Cost_i$) to per-transition ($Cost_{i,j}$)

- Changed Decision Variable
  - $Tx_{i,j,m,t}$ = Number of brigades that replaced vehicle type *i* with vehicle type *j* for mission *m* in year *t*

Transition-Based Model

- New Decision-based expression
  - $BrigInService_{i,m,t}$ = Number of brigades using vehicle *i* for mission *m* in year *t*

$$BrigInService_{i,m,t} = InitialPopulation_{i,m,t} + \sum_{\substack{j,t^*: \\ t^* \le t \\ IsValidTx_{j,i,m}}} Tx_{j,i,m,t^*} - \sum_{\substack{j,t^*: \\ t^* \le t \\ IsValidTx_{i,j,m}}} Tx_{i,j,m,t^*}$$

Transitions into i

Transitions out of i

- Objective Function: Maximize cumulative fleet performance

$$\max \sum_{i,m,t} BrigInService_{i,m,t} Q_m \alpha_{i,m}$$

Production Model

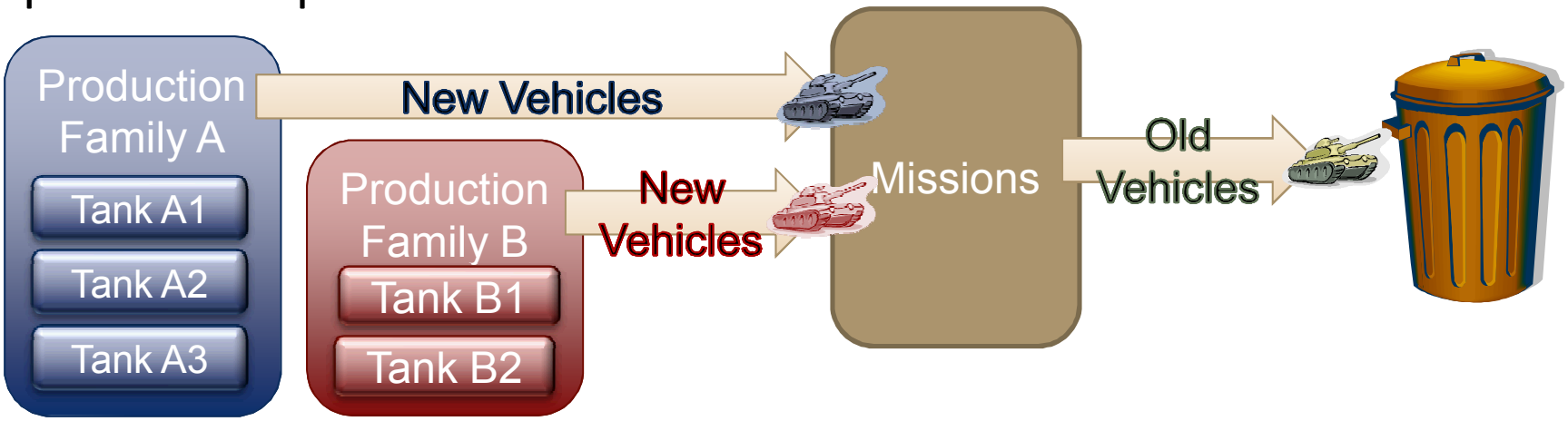
- Initial Production Model Was Intentionally Simple

- Issues
  - Gaps and excessive variability in production rates
  - No production limits among collections of vehicles
  - Poor production cost modeling

  - Can’t repurpose vehicles, exchange between missions
  - Can’t pre-purchase partial brigade quantities of vehicles

Production Families

- A production family is a collection of vehicle types with shared production parameters



- Production Family Characteristics
  - Upper and lower production rate limits
  - No production gaps allowed
  - Shared production cost model
    - Startup costs
    - Per-period costs

Production Families

- Family-related input parameters:
  - $ActiveCost_p$ – A cost incurred every year production family *p* is active (producing vehicles)
  - $StartupCost_{p,n}$ – A cost that is incurred n time periods after family *p* first becomes active. A multi-year startup cost profile for family *p* can be made using multiple values of *n*. Also, *n* can be negative.
  - $MaxVariance_p$ – The maximum variation in production rate for family *p*.

- Production family decision variables
  - $fMedianProductionRate_p$ – The median production rate for family *p*.
  - $bProdFamActive_{p,t}$ - Whether production family *p* is active at time *t*.
  - $bProdFamStartup_{p,t}$ - Whether production family *p* first became active at time *t.*

Production Family Expenditures

- $StartupCharge_{p,t}$ – The expense incurred in time *t* due to starting production of family *p*.

$$StartupCharge_{p,t} = \sum_{t^*} bProdFamStartup_{p,t^*} \cdot StartupCost_{p,t-t^*}$$

- $ActiveCharge_{p,t}$ – The expense incurred in time *t* due to family *p* being active.

$$ActiveCharge_{p,t} = bProdFamActive_{p,t} \cdot ActiveCost_p$$

Production Variance

- Ensure production stays below max variance threshold

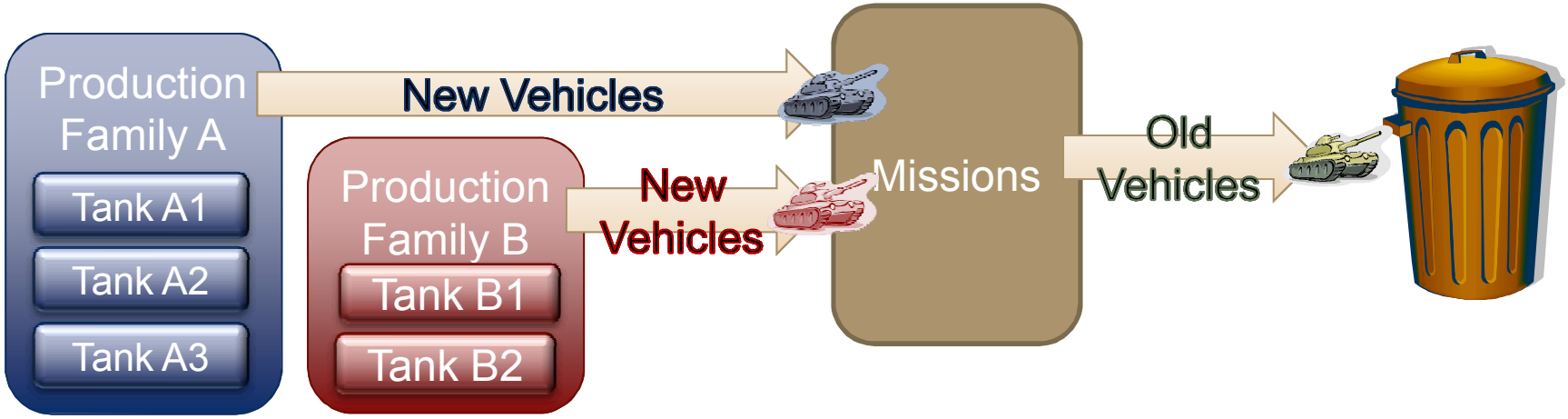
$$\forall p, t \quad \sum_{i \in Family_p} NumProduced_{i,t} \leq \left(1 + 0.5 * MaxVariance_p\right) * fMedianProductionRate_p$$

- Ensure production stays above min variance threshold

$$\forall p, t \quad \sum_{i \in Family_p} NumProduced_{i,t} \geq \left(1 - 0.5 * MaxVariance_p\right) * fMedianProductionRate_p - \left(1 - bProdFamActive_{p,t}\right) * TotalVehiclePopulation$$

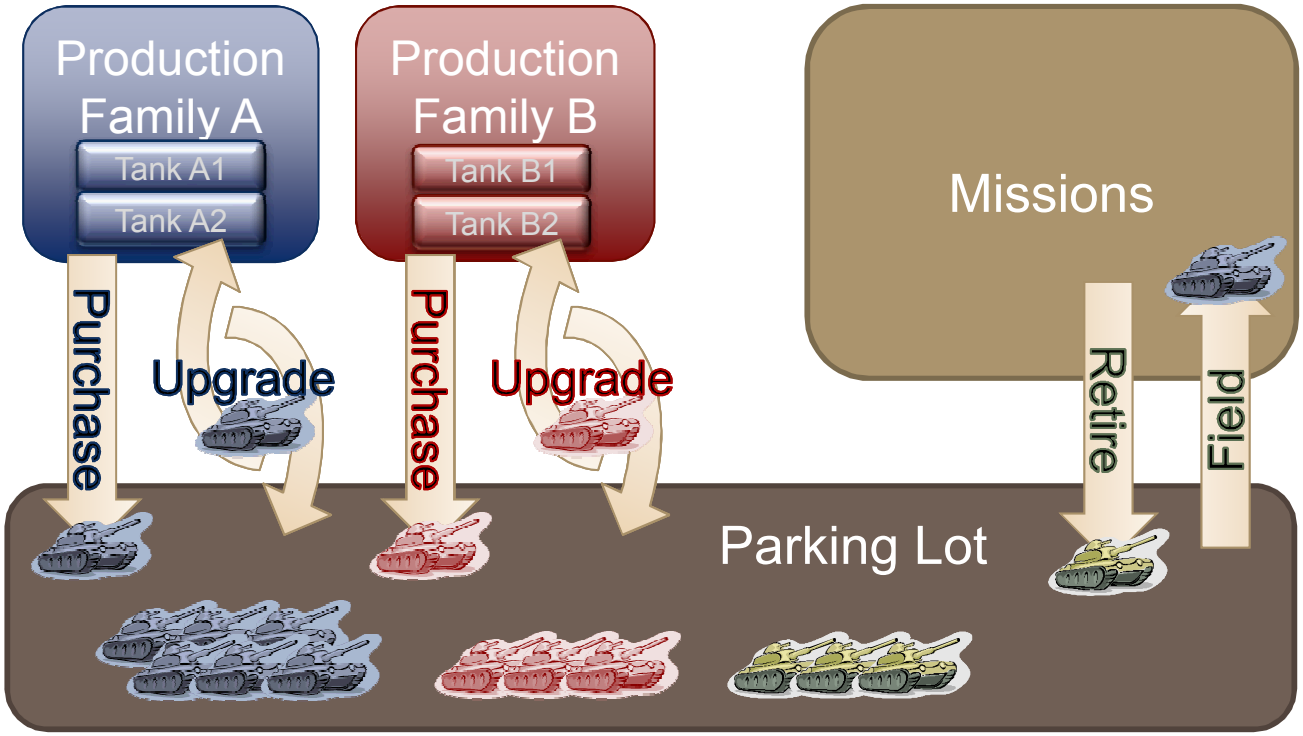
Revising the Fielding Model

- Although the production model improved, the vehicle "flow" model was still too limited
  - Can't repurpose vehicles, exchange between missions
  - Can't produce partial brigade quantities of vehicles
  - Can't pre-purchase vehicles



The Parking Lot

- These issues were resolved by decoupling production and fielding
- Implemented by introducing a “parking lot”
  - New vehicles do not need to be fielded immediately
  - Retired vehicles can be repurposed by other missions
  - Vehicle upgrades and modifications can take place while out of service



Parking Lot Inventory

$$NumVehInStorage_{i,t} = InitialVehInventory_i$$

$$+ \sum_{t^* \le t} NumPurchased_{i,t^*}$$ ← New production

$$+ \sum_{\substack{j,m,t^*: \\ (i,j,m) \in ValidTx \\ t^* \le t}} Tx_{i,j,m,t^*} * Q_m$$ ← Removed from missions

$$+ \sum_{\substack{j,t^*: \\ (j,i) \in ValidUpg \\ t^* \le t}} NumUpgrades_{j,i,t}$$ ← Converted from something else into vehicle *i*

$$- \sum_{\substack{j,m,t^*: \\ (j,i,m) \in ValidTx \\ t^* \le t}} Tx_{j,i,m,t^*} * Q_m$$ ← Fielded to missions

$$- \sum_{\substack{j,t^*: \\ (i,j) \in ValidUpg \\ t^* \le t}} NumUpgrades_{i,j,t}$$ ← Converted from vehicle *i* into something else

Additional Customer-Driven Features

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- Research investments as prerequisites for vehicle availability
- Administrative and delivery delays
- Initial production profiles / production ramp-up
- Cross-mission synchronized transitions
- Minimum transition densities
- Mission Priority Tiers

Model Development Recommendations

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- Don’t try to duplicate reality.
- Start with as simple a model as possible.
- Customer feedback is vital. Actively seek feedback frequently.
- Prioritize – capture what matters most first.
- Work iteratively, in small chunks