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Enhancing Multi-Period, Multi-Commodity, Multi-Modal Network Flow Optimization in the Mekong Delta

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University of Kent

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Introduction

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Introduction

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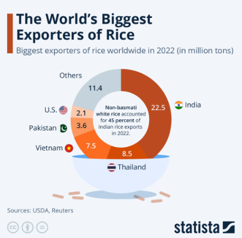
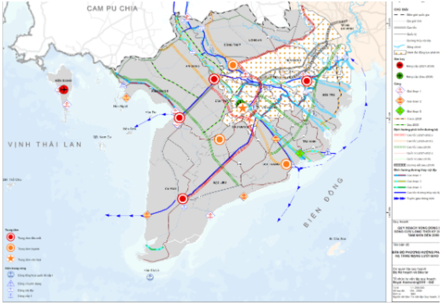
- **Mekong Delta:** World's 10th-largest river network (8th in annual flow), vital for Vietnam's economy.
- **Challenge:** Fragmented road-waterway systems increase costs and delay goods/passenger movement.
- **Research Goal:** Develop a multi-period optimization model to:
  - Minimize total costs (infrastructure + transport + mode-switching).
  - Guide hub/route investments over 15 years (3 phases).
- **Impact:** Benefit 20M+ residents, boost regional trade, and support the Sustainable Development Goals of the UN.



Introduction

Challenge: Fragmented road-waterway systems increase costs and delay goods/passenger movement.

- **Transport Network** Complex multimodal system (road, waterway).
- **Goods and Passengers** (rice, Shrimp/Fish and Fruits/Vegetables)



Problem Assumptions & Key Components

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Problem Assumptions & Key Components

- **Core Assumptions:**
  1. *Multimodal network:* Road (fast, high cost) + Waterway (slow, low cost).
  2. *Time horizon:* 3 periods (5 years each; total 15 years).
  3. *Commodity types:* Passengers, Rice (bulk), Shrimp/Fish (frozen), Fruits/Vegetables (perishable).
  4. Decisions:
     - *Hub selection:* Build/upgrade ports and warehouses (e.g., Can Tho, An Giang).
     - *Route investment:* Construct/upgrade roads/waterways.
     - *Flow allocation:* Assign paths for goods/passengers.
- **Cost components:** Infrastructure (hub/arc upgrades), transportation (origin-hub-destination), mode-switching, and hub service.

Mathematical Notation & Sets

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Key Sets

- $\mathcal{T} = \{1, 2, 3\}$: Time periods (5-year stages)
- $\mathcal{N}$: Nodes (e.g., An Giang, HCMC)
- $\mathcal{H} \subseteq \mathcal{N}$: Hub locations (e.g., Can Tho)
- $\mathcal{A}$: Arcs (road/waterway links)
- $\mathcal{G} = \{\text{passenger, rice, fish, vegetables/fruits}\}$: Commodities
- $\mathcal{K}$: Origin-destination pairs
- $\mathcal{P}_{gk}$: Paths for commodity g and OD pair k
- $\mathcal{L}_h, \mathcal{L}_a$: Hub/arc capacity levels

Mathematical Notation & Sets

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Parameters

$f^t_{l_h}, \widetilde{f}^t_{l_a}$	Hub and Arc expansion cost (level l_h, period t)
c^t_a	Transport cost on arc a
$\widetilde{c}^t$	Mode-switching cost at hubs
w^t_{gk}	Demand for commodity g (OD pair k)
Δ_{l_h}, κ_p	Hub capacity at level l_h and Mode-switches on path p

Decision Variables

$y^t_{hl_h}, \widetilde{y}^t_{al_a} \in \{0, 1\}$	Hub capacity upgrade and Arc capacity upgrade are selected
$v^t_{pg} \in [0, 1]$	Fraction of flow on path p
$u^t_h, x^t_a \geq 0$	Flow through hub h and Flow through arc a

Optimization Model & Constraints

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Optimization Model & Constraints

Objective Function

$$\min Z = \underbrace{\sum_{t,h,l_h} f^t_{l_h} \Delta_{l_h} y^t_{hl_h}}_{\text{Hub cost}} + \underbrace{\sum_{t,a,l_a} \widetilde{f}^t_{l_a} \widetilde{\Delta}_{l_a} \widetilde{y}^t_{al_a}}_{\text{Arc cost}} + \underbrace{\sum_{t,h} \overline{c}^t_h u^t_h}_{\text{Hub service}} + \underbrace{\sum_{t,g,k,p} c^t_p w^t_{gk} v^t_{pg}}_{\text{Transport}}$$

where $c^t_p = \sum_{a \in A_p} c^t_a + \kappa_p \widetilde{c}^t$

Key Constraints

1. Flow balance for commodities.
2. Hub and arc capacity limits.
3. Construction logic (one capacity level per hub/arc).

Graph Transformation for Multimodal Network

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Graph Transformation for Multimodal Network

Challenge: Model mode-switching (road ↔ water) at hubs efficiently.
Solution: Convert to single-arc network using artificial nodes:

- Step 1: Split each physical node u into two mode-specific nodes:
  - u^1 (accessed by road), u^2 (accessed by water).
- Step 2: Create directed arcs:
  - Same-mode arcs: $u^1 \rightarrow v^1$ (road-road), $u^2 \rightarrow v^2$ (water-water).
    Cost = Transportation cost only.
  - Mode-switch arcs: $u^1 \rightarrow v^2$ (road→water), $u^2 \rightarrow v^1$ (water→road).
    Cost = Transportation cost + mode-switching cost ($\widetilde{c}^t$).

Graph Transformation for Multimodal Network

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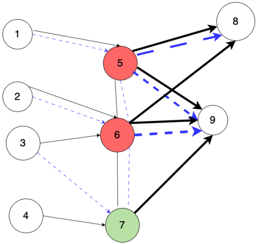

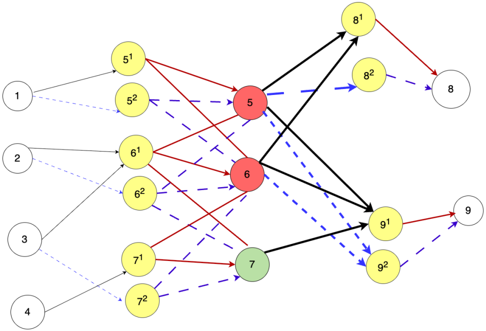

Advantage:

- Simplifies path-cost calculation.
- Captures mode transitions explicitly.

Toy Example & Results

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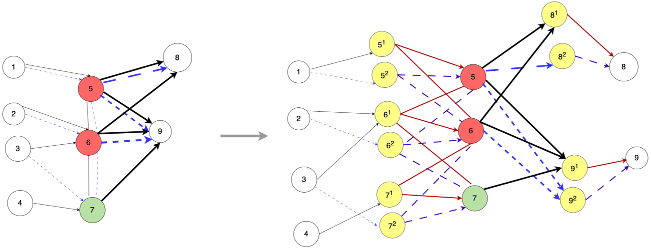
Toy Example & Results

Network Setup:

- Nodes: 9 nodes 1,2,3,4,...,9
- Commodities:
  - Passengers: (1->8)
  - Rice: (1->8), (2->8)
  - Fish: (3-8), (3->9)
  - Vegetable: (4->8), (4-9)
- Upgrades:
  - Hub 5, Hub 6
  - Arcs: 5->8, 5->9, 6->9, 7->9

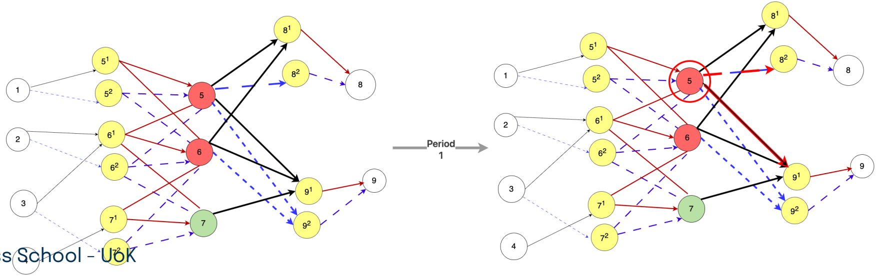


Optimization Results

Simulation Setup: Solver: Gurobi 10.0; demand growth: 20% per period; Network scale: 9 nodes –3 hubs, 33 arcs.

Strategic Upgrade Timeline– Period 1 Upgrades:

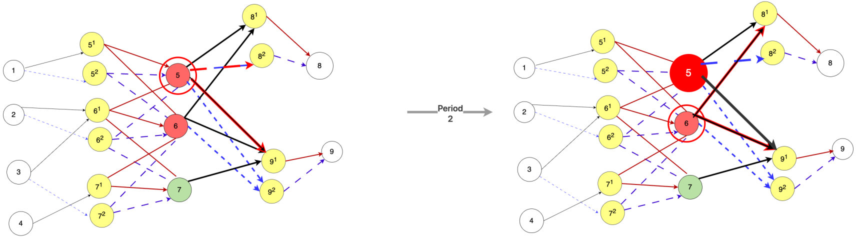
Component	Action
Hub 5	Upgraded
Arc $5 \longrightarrow 8^{water}$	Upgraded
Arc $5 \longrightarrow 9^{road}$	Upgraded



Optimization Results

Strategic Upgrade Timeline– Period 2 Upgrades:

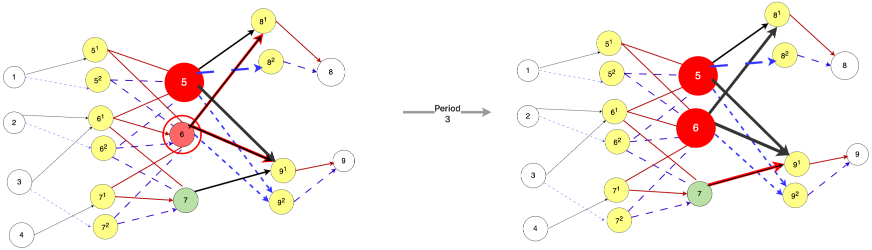
Component	Action
Hub 6	Upgraded
Arc $6 \longrightarrow 8^{road}$	Upgraded
Arc $6 \longrightarrow 9^{road}$	Upgraded



Optimization Results

Strategic Upgrade Timeline- Period 3 Upgrades:

Component	Action
Hubs	None
Arc $7 \longrightarrow 9^{road}$	Upgraded



Future Application & Conclusion

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Real-World Network Implementation

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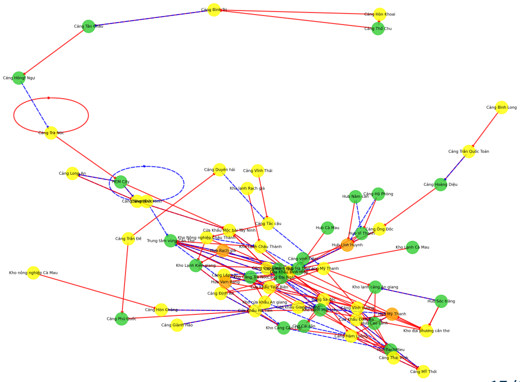
Extended Model Application:

- Scale:
  12 provinces, 64 hubs, 162 arcs
- Time: 3 periods (15 years total)
- Commodities:
  Rice, Fish, Vegetables, Passengers
- Multimodal Network:
  Road + Waterway integration

Mạng Lưới Trước Nâng Cấp (Mekong Delta)



Strategic Implementation Phases

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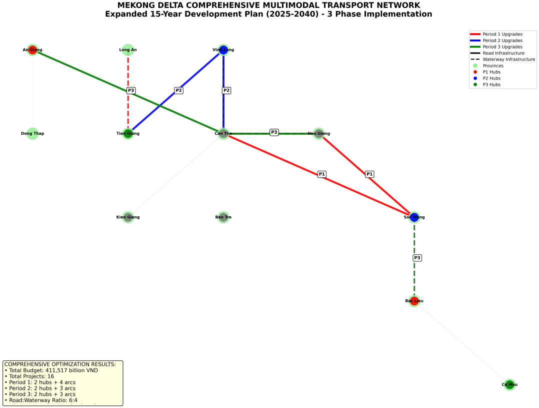
With sample infrastructure costs, transport tariffs, demand patterns:



Future Application & Conclusion

Conclusion:

- Research proposes a model for optimizing multimodal transport networks.
- Strategic investment reduces logistics costs while enhancing regional connectivity.
- Ready for real-world implementation with 12 provinces and 64 hubs

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Thank You for Listening!

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