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Resilient Logistics Flow Routing in Hyperconnected Networks

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Presentation Agenda

- Motivation
- Resilient Flow Route Generation Algorithms
  - Basic Resilience-Optimized Route Generation Algorithm
  - Adaptive Resilience-Optimized Route Generation Algorithm
- Case Study Results & Discussion
  - Efficiency Comparison
  - Resiliency Comparison
- Future Work & Research

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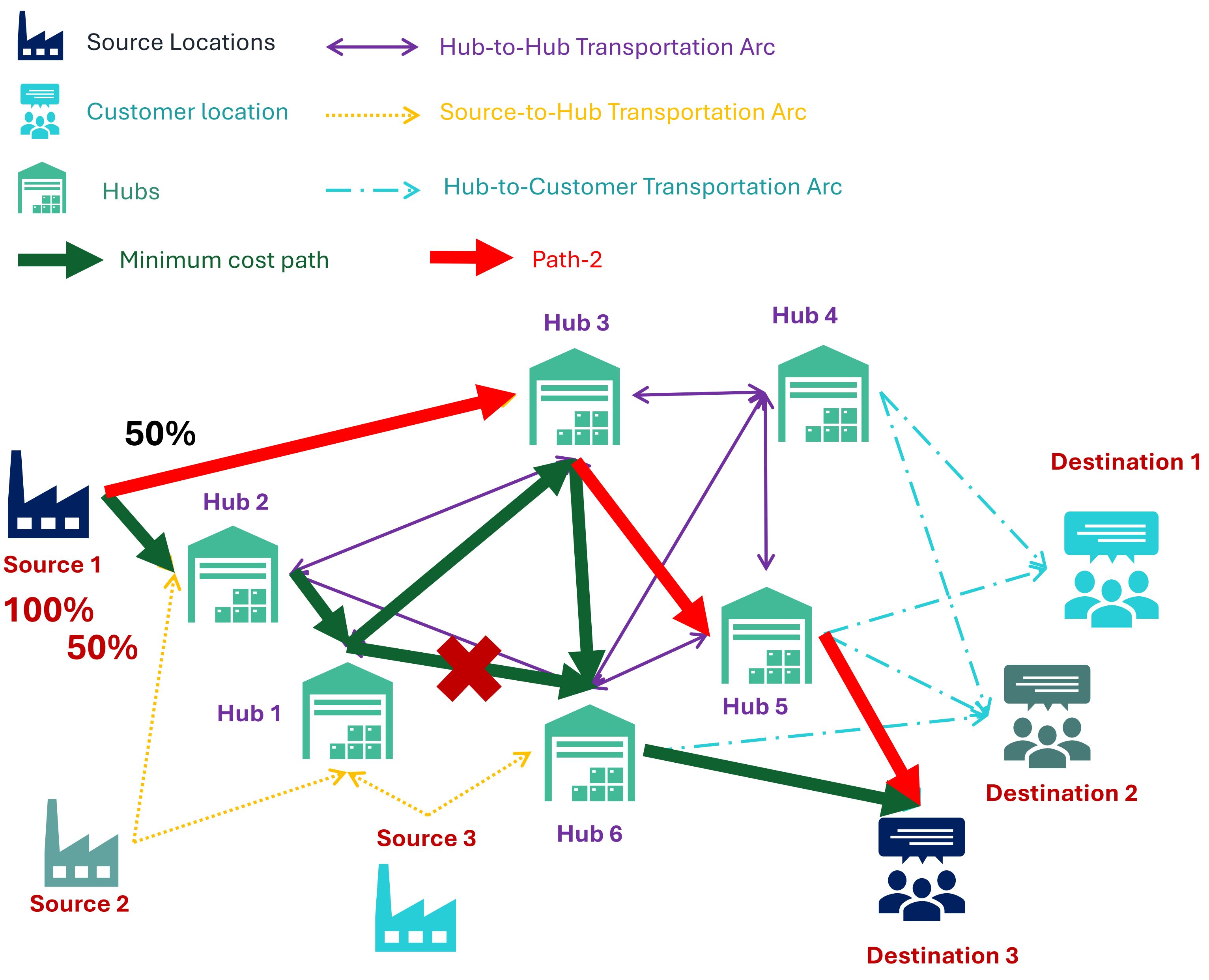
Motivation

- Set of logistics companies deliver commodities to customers across a geographical region through **Physical Internet Enabled Hyperconnected Hub Networks.**
- They are interested in **devising commodity flow routes** that are **efficient in nominal situations** and **resilient under disruptions**.
- In the **absence of disruptions**, the route follows the **minimum cost-path** to minimize the operational expenses.
- To be **resilient under disruptions**, several works employed strategies such as **network topology optimization** and **dynamic commodity routing.**
- These approaches work well only in **networks with limited degree of hyperconnectivity** - fails to scale to dense networks and the **entire flow remains to be affected by disruptions**.
- To **reduce the proportion of flow** impacted by disruptions, we can **strategically route commodities** in **pre-disruption phase.**



"Resilience-Optimized Routes"

Resilient Flow Route Generation

- **Underlying premise –** When disruption occurs and a path is rendered unavailable, only a fraction of commodity delivery is affected

- We present two algorithms to generate such **Resilience-Optimized commodity delivery routes** in **Hyperconnected Networks**

Basic Resilience-Optimized

Adaptive Resilience-Optimized

“Employs the principle of distributing the commodity flow across multiple edge-disjoint paths” [1]

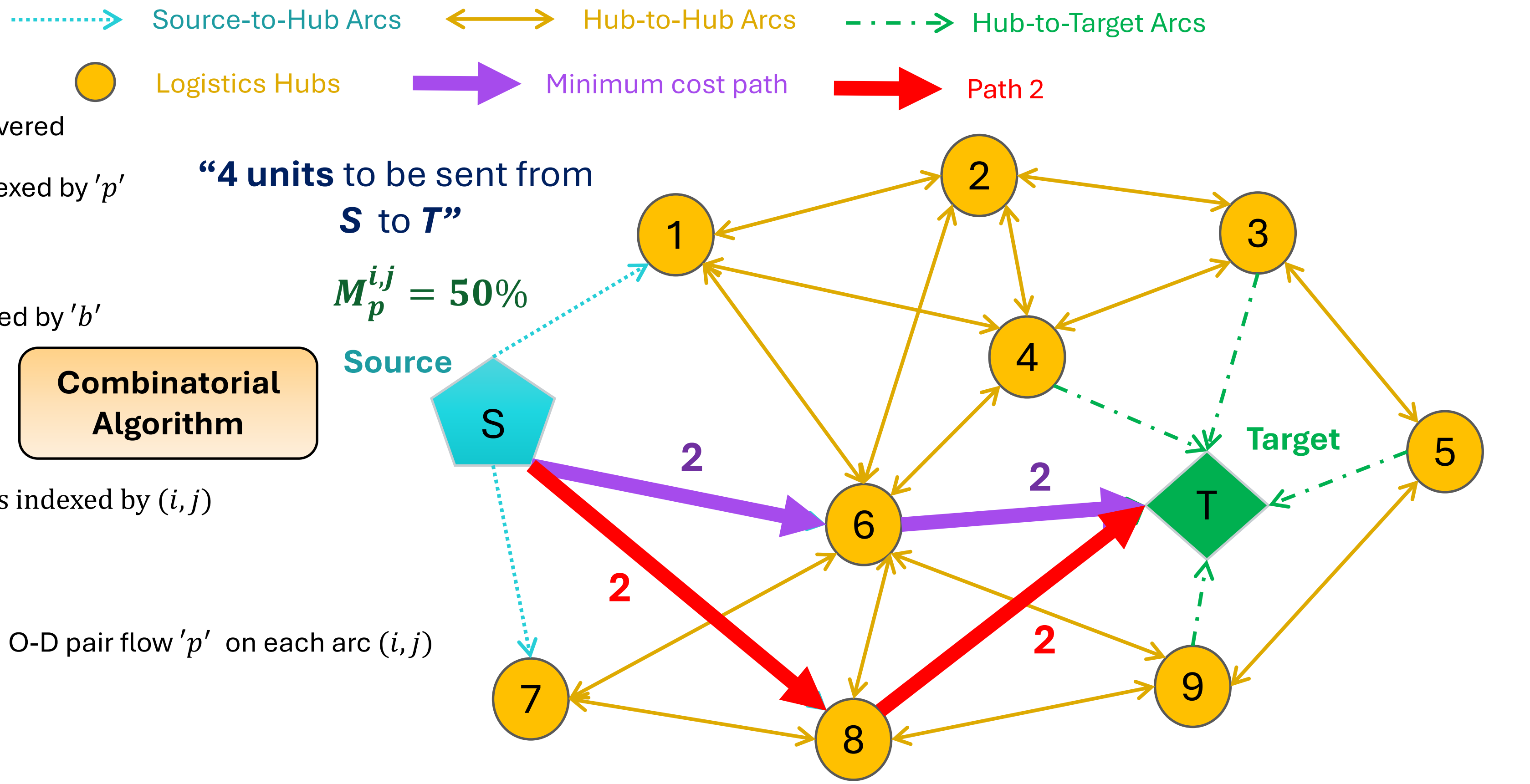
Source: [1] *Kulkarni, O., Cohen, Y. M., Dahan, M. & Montreuil, B., 2021. Resilient hyperconnected logistics hub network design., 8th International Physical Internet Conference*

Basic Resilience-Optimized Route Generation Algorithm

Distribute commodity flows across multiple edge-disjoint paths between each O-D pair

- **Input Sets and Data Parameters**
  - $\mathcal{S}$: Set of locations where demand originates
  - $\mathcal{T}$: Set of locations where commodities are delivered
  - $\mathcal{P} \subseteq \mathcal{S} \times \mathcal{T}$: Set of Origin-Destination Pairs indexed by $'p'$
  - D_p^1 : Demand of O-D pair $'p'$
  - $\mathcal{B}$: Set of logistics companies (or) brands indexed by $'b'$
  - $\mathcal{P}_b \subseteq \mathcal{P}$: Set of O-D pairs of each brand $'b'$
  - $\mathcal{H}$: Set of logistics hubs indexed by $'h'$
  - $\mathcal{A} \subseteq (\mathcal{S} \cup \mathcal{T} \cup \mathcal{H})^2$: Set of transportation arcs indexed by (i, j)
  - C_{ij} : Cost estimates on transportation arc (i, j)
  - $M_p^{i,j} \in [0, 100]$: Maximum proportion of each O-D pair flow $'p'$ on each arc (i, j)

Combinatorial Algorithm



The aim here is……

"To devise $k_p = \lceil 100/M_p^{i,j} \rceil$ edge-disjoint paths for each O-D pair"

"Compute these **independently for each O-D pair**"

"However, in practice, **arc capacity for each O-D pair is not sufficient**"

A company or brand has arc restriction for all its O-D pairs together because of the **associated contracts with truckers** for their travel on the arc

"NOT CAPTURED IN THIS MODEL" → **ADAPTIVE RESILIENCE-OPTIMIZED**

Adaptive Resilience-Optimized Route Generation Algorithm

"Additional capacity constraint on each arc **based on brand's flow**"

- **Input Sets and Data Parameters**
  - $\mathcal{S}$: Set of locations where demand originates
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  - $\mathcal{P} \subseteq \mathcal{S} \times \mathcal{T}$: Set of Origin-Destination Pairs indexed by $'p'$
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  - C_{ij} : Cost estimates on transportation arc (i, j)
  - D_p : Demand of O-D pair $'p'$
  - $D_b = \sum_{p \in \mathcal{P}_b} D_p$: Total demand of brand $'b'$
  - $M_p^{i,j} \in [0, 100]$: Maximum proportion of each O-D pair $'p'$ on each arc
  - $N_b^{i,j} \in [0, 100]$: Maximum proportion of brand $'b'$ flow on each arc

Source-to-Hub Arcs — Available Hub-to-Hub Arcs — Hub-to-Target Arcs

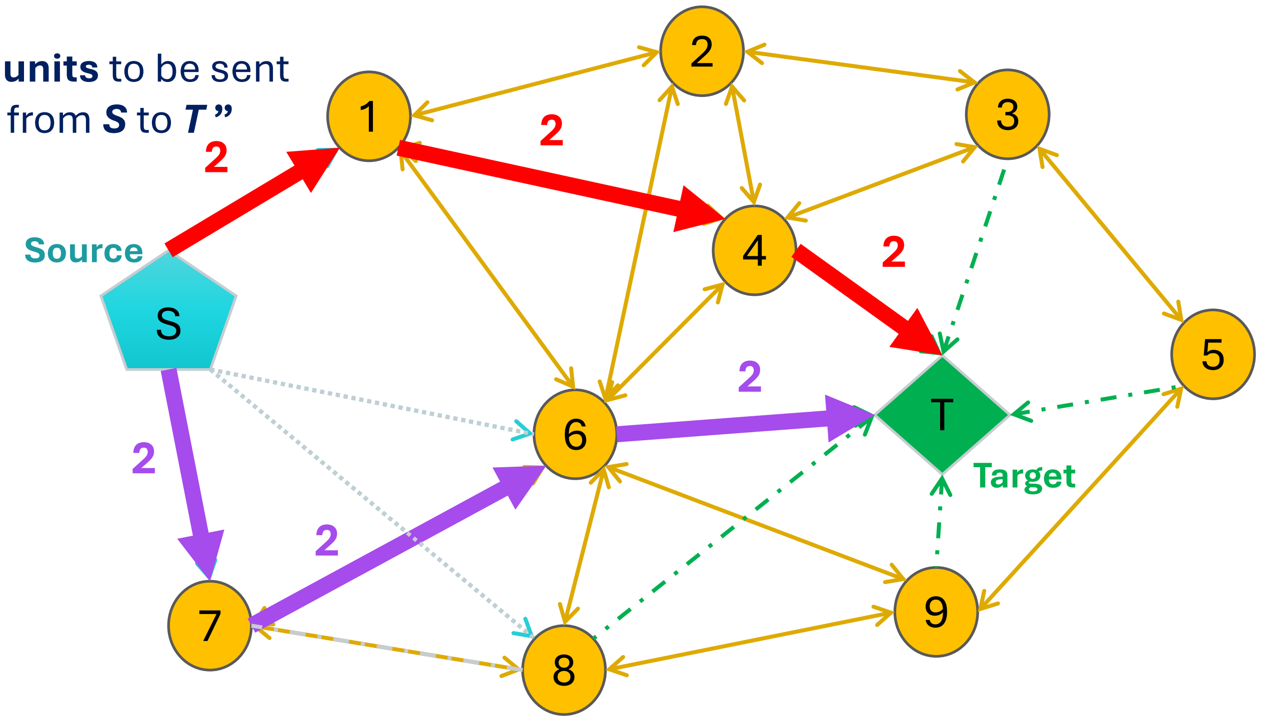
Logistics Hubs — Brand-based capacity depleted arcs

Minimum cost path — Path 2

$$M_p^{i,j} = 50\%$$

Combinatorial Algorithm

"**4 units** to be sent from ***S*** to ***T***"



"Independence of devising commodity flows **present at brand level** but not for each O-D pair separately"

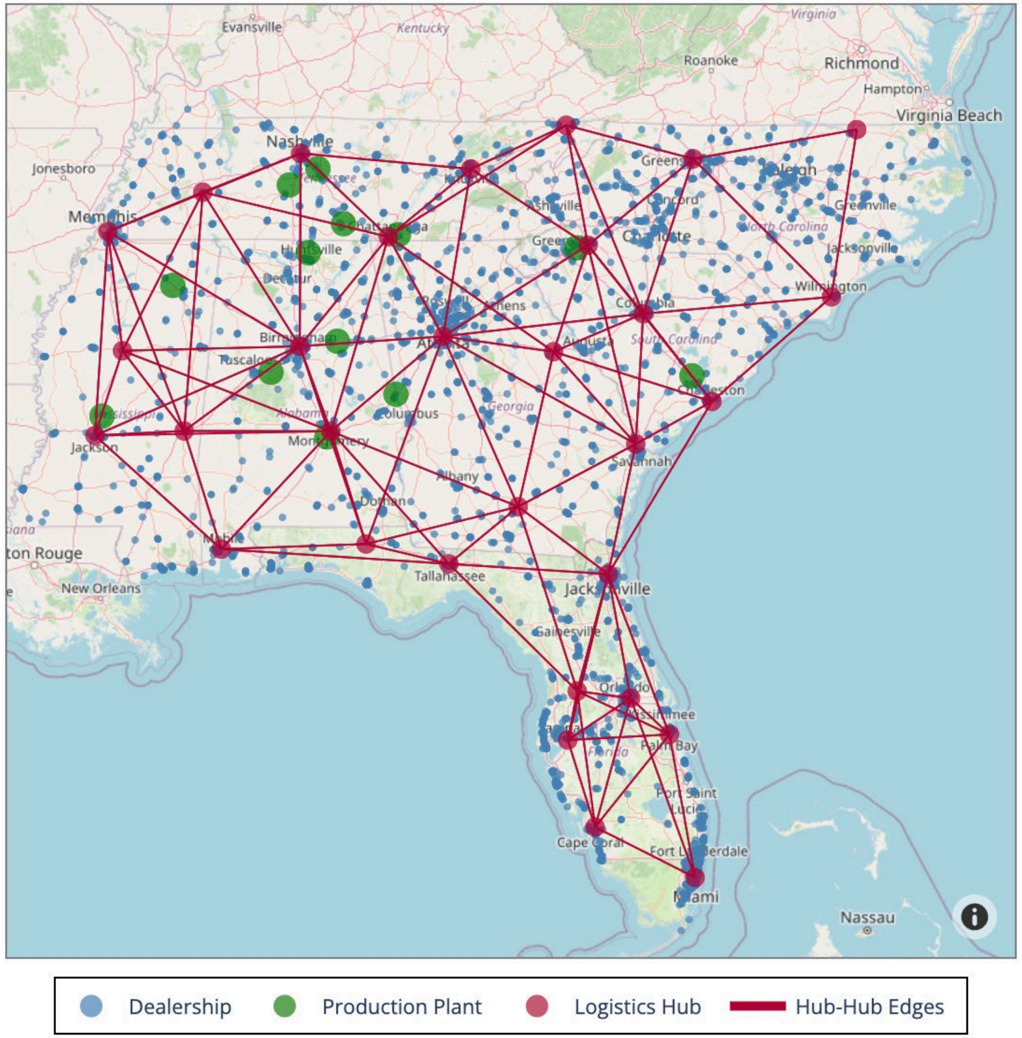
Additional capacity restriction on each transportation arc leads to **distribution of commodity flow** to even **larger number of edge-disjoint paths**

Process the O-D pairs that belong to a brand in decreasing order of their associated demand and process the brand in decreasing order of associated demand

"MORE RESILIENT PATHS"

Case Study Results & Discussion

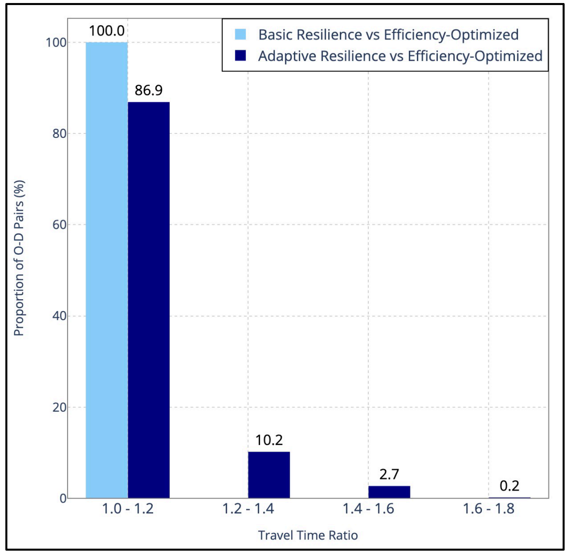
Design commodity flow routes for finished vehicle logistics from production plants to dealerships across US Southeast through hyperconnected hub network employing proposed algorithms



Source: [2] *Grover, N., Shaikh, S. J., Faugère, L. & Montreuil, B., 2023. Surfing the Physical Internet with Hyperconnected Logistics Networks. 9th International Physical Internet Conference*

Case Study Results & Discussion

Efficiency Comparison



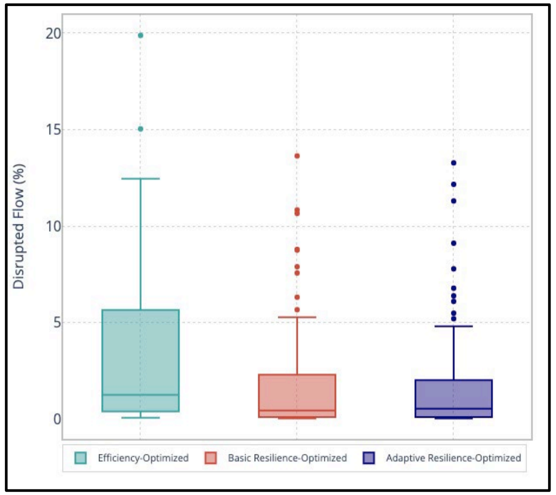
- **Efficiency metric:**

$$\sum_{OD\ paths} \frac{\text{Path Travel Time} \ * \text{Path Flow}}{(\text{Min−cost Path Travel Time}) * (\text{Min−cost Path Flow})}$$

- **Basic Resilience-Optimized**: The **induced travel time of all O-D pairs is increased by < 20%** of efficiency optimized route(s).
- **Adaptive Resilience-Optimized: ~13%** of O-D pairs show increase by **>20%** and **3%** of O-D pairs **show increase by >40% on travel time**.

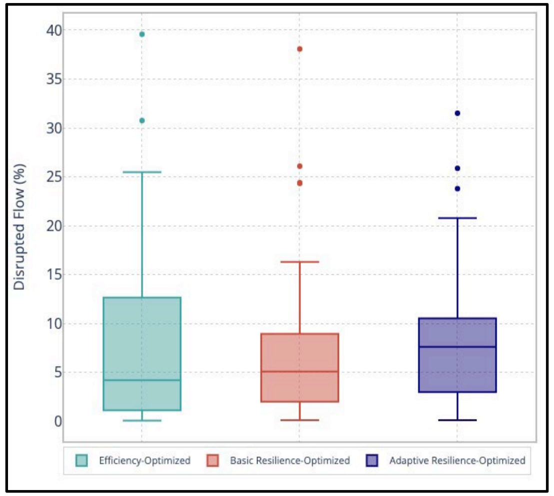
Prioritizing O-D pairs with higher flows within each brand, **the O-D pairs with lower flow have to take considerably longer routes**

Resiliency Comparison



1- Edge Worst case Disruption

- **Efficiency-Optimized:** Distribution of flow for all O-D pairs in network is **highly concentrated on a fewer number of critical edges.**
- **Basic Resilience-Optimized:** The proportion of flow is **well-distributed across the edges** and any disruption in these edges **affects a lesser proportion of overall flow**.
- In **Adaptive Resilience-Optimized**, flow is evenly distributed to multiple edges enabling a **major proportion of flow** to meet service time targets **even under such worst-case disruptions.**



1- Hub Worst case Disruption

- **Efficiency-Optimized:**
  - Distribution of flow is **highly concentrated on a few hubs** with **almost 40%** flowing through 1 hub.
  - On **an average higher proportion of O-D flow is likely to be affected under worst case hub disruptions**.
- In **Adaptive Resilience-Optimized**, despite achieving higher resilience under edge disruptions **it introduces a trade-off**.

"Selected edge-disjoint paths **exhibit more intersections of nodes**, rendering the system **less resilient under hub disruptions** compared to **basic-resilience optimized"**

Future Work & Research

1. These algorithms, although scalable, are still heuristic ways to devise resilience-optimized commodity delivery routes. The first avenue is to explore **optimization-based modeling** framework and **devise exact solution approaches** for it.

2. Instead of devising edge-disjoint commodity delivery paths, **non-edge-disjoint paths** can be computed

    - Although **less capable of sustaining disruptions**, is indeed **more efficient in nominal operating conditions**.
    - This will require **exponential-sized optimization models** and **sophisticated solution techniques** such as **column generation** to devise good quality routes.

3. Finally, regarding evaluation of such routes, a more **comprehensive set of disruption experiments** can be conducted.

    - This could involve **simulating other types of disruption scenarios** such as multiple edge and hub disruptions, localized disruptions, and adversarial type of disruptions.

4. Devising comprehensive cost function considering greenhouse gas emissions and compare between resilient and non-resilient algorithms in presence and absence of disruptions.

Any comments, questions and suggestions are most welcome

Thank You !