

Speed-aware network design

A parametric optimisation approach

Ugo Rosolia, Marc Bataillou Almagro, George Iosifidis, Amit Kumar, Georgios Paschos

Outline

- ▶ Motivation
- ▶ Problem formulation
- ▶ Solution strategy
- ▶ Results

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Middle Mile Network Design

Origin #1



Origin #2



Destination



Middle Mile Network Design



Consolidation Hub



Middle Mile Network Design



Middle Mile Network Design



Key decisions

1. Connectivity, i.e., buildings to connect.
2. Timing, i.e., trucks departure times.

Middle Mile Network Design



Key decisions

1. Connectivity, i.e., buildings to connect.
2. Timing, i.e., trucks departure times.

Objectives

1. Reduce cost.
2. Minimize carbon emissions.
3. Maximize delivery speed.

Middle Mile Network Design



Origin



Consolidation Hub



Destination

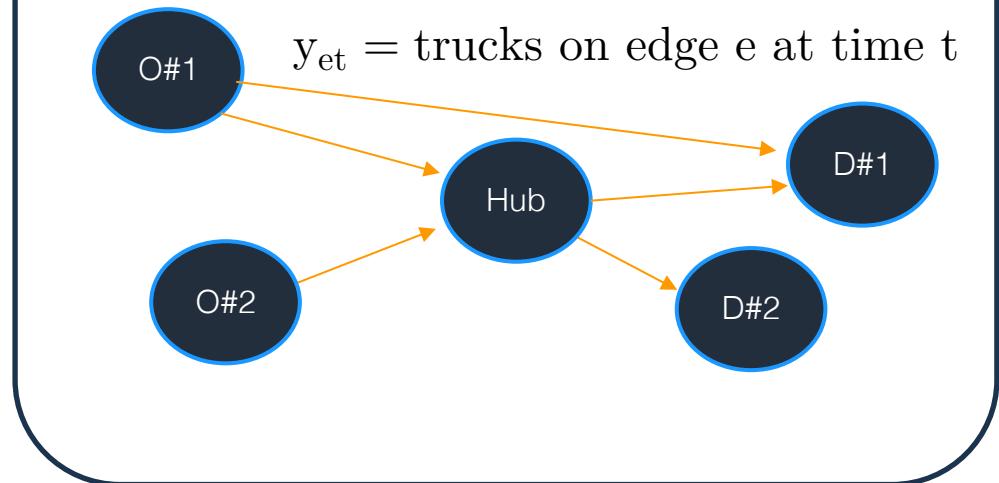
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Time-expanded network flow problem



Middle Mile Network Design



Consolidation Hub



Destination



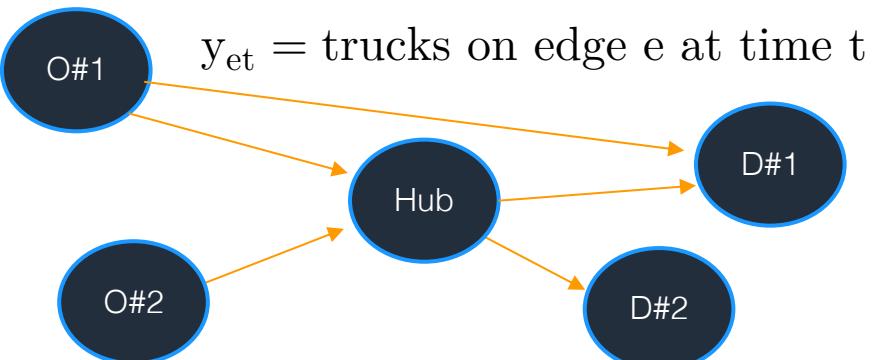
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Time-expanded network flow problem



Intractable at Amazon's scale!

Why considering speed?

Why considering speed?

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Glass Carafe Shatterproof SAN Carafe

Color: Chrome



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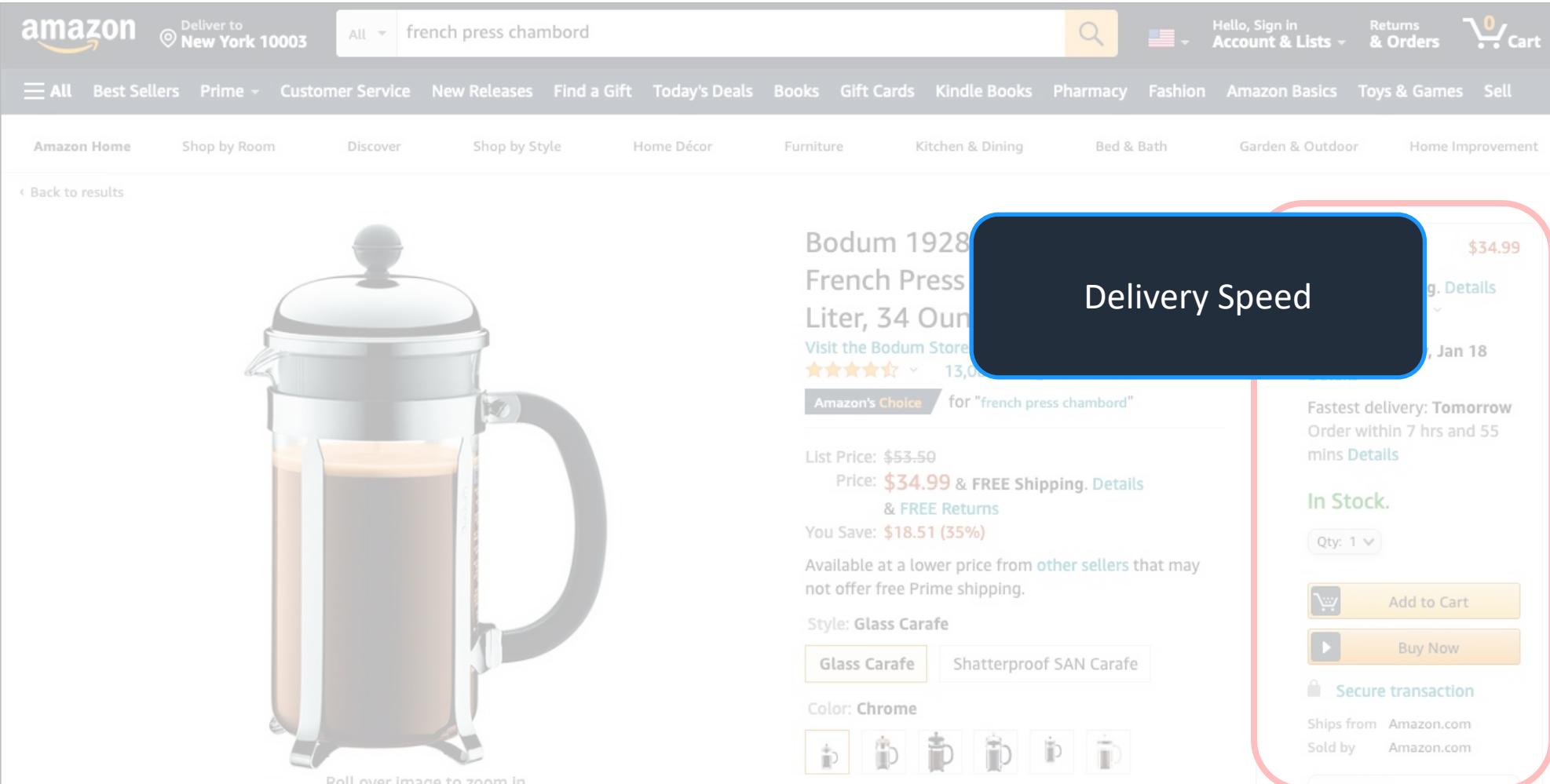
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Delivery Speed

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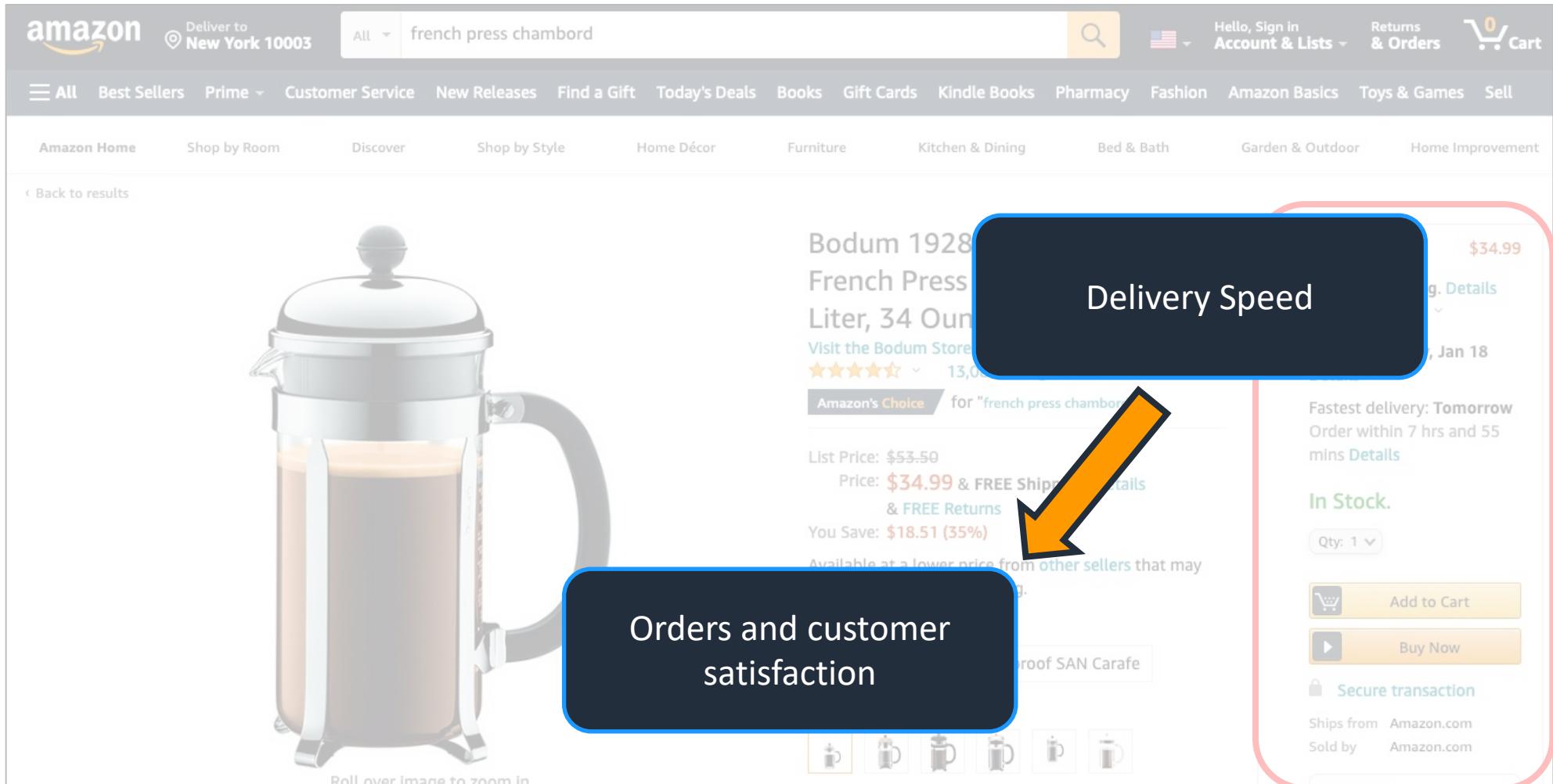
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French Press, 34 Ounce, 1 Liter, 34 Ounce

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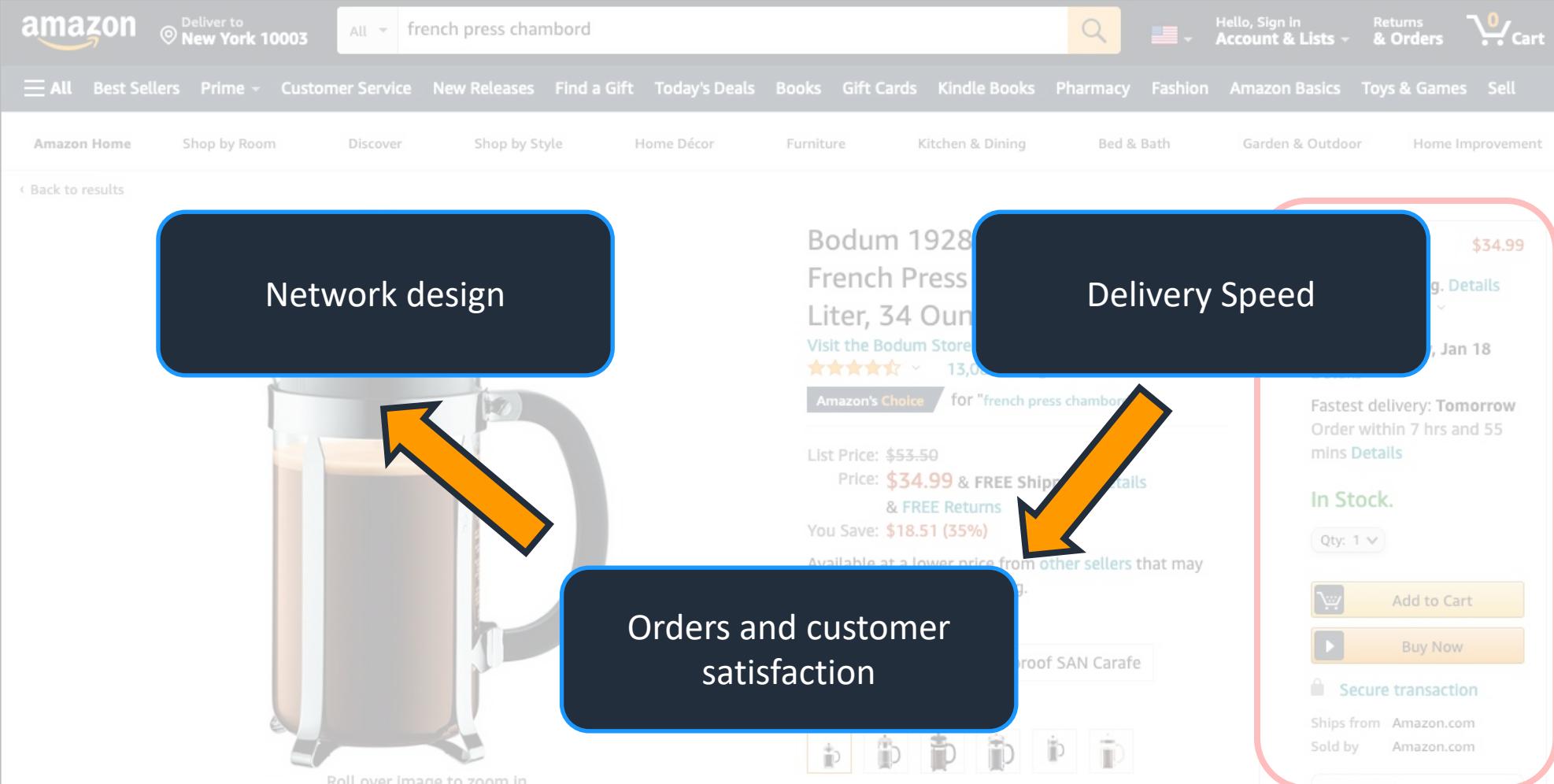
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Delivery Speed

Orders and customer satisfaction

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Why considering speed?



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Network design

Delivery Speed

Orders and customer satisfaction

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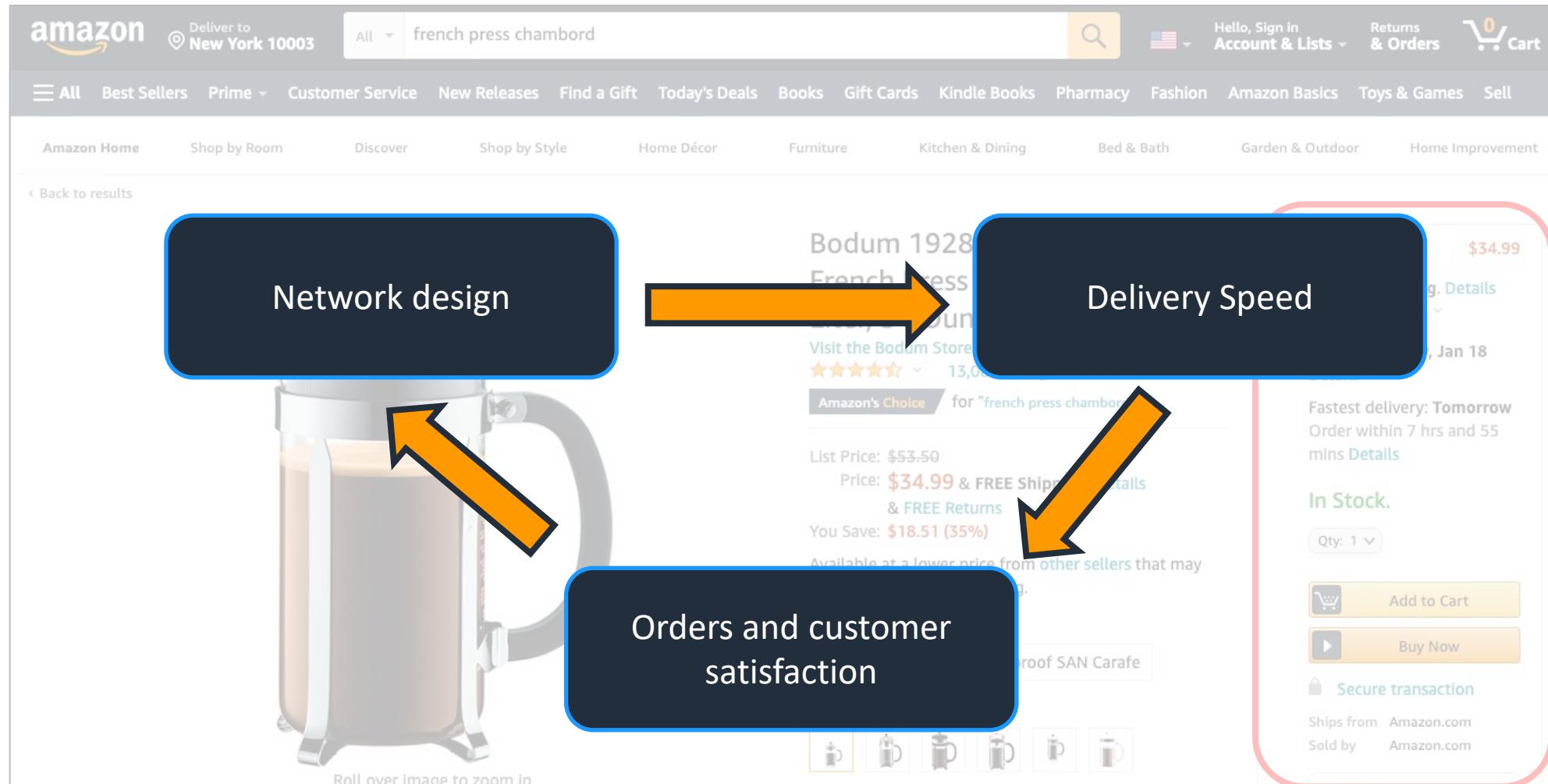
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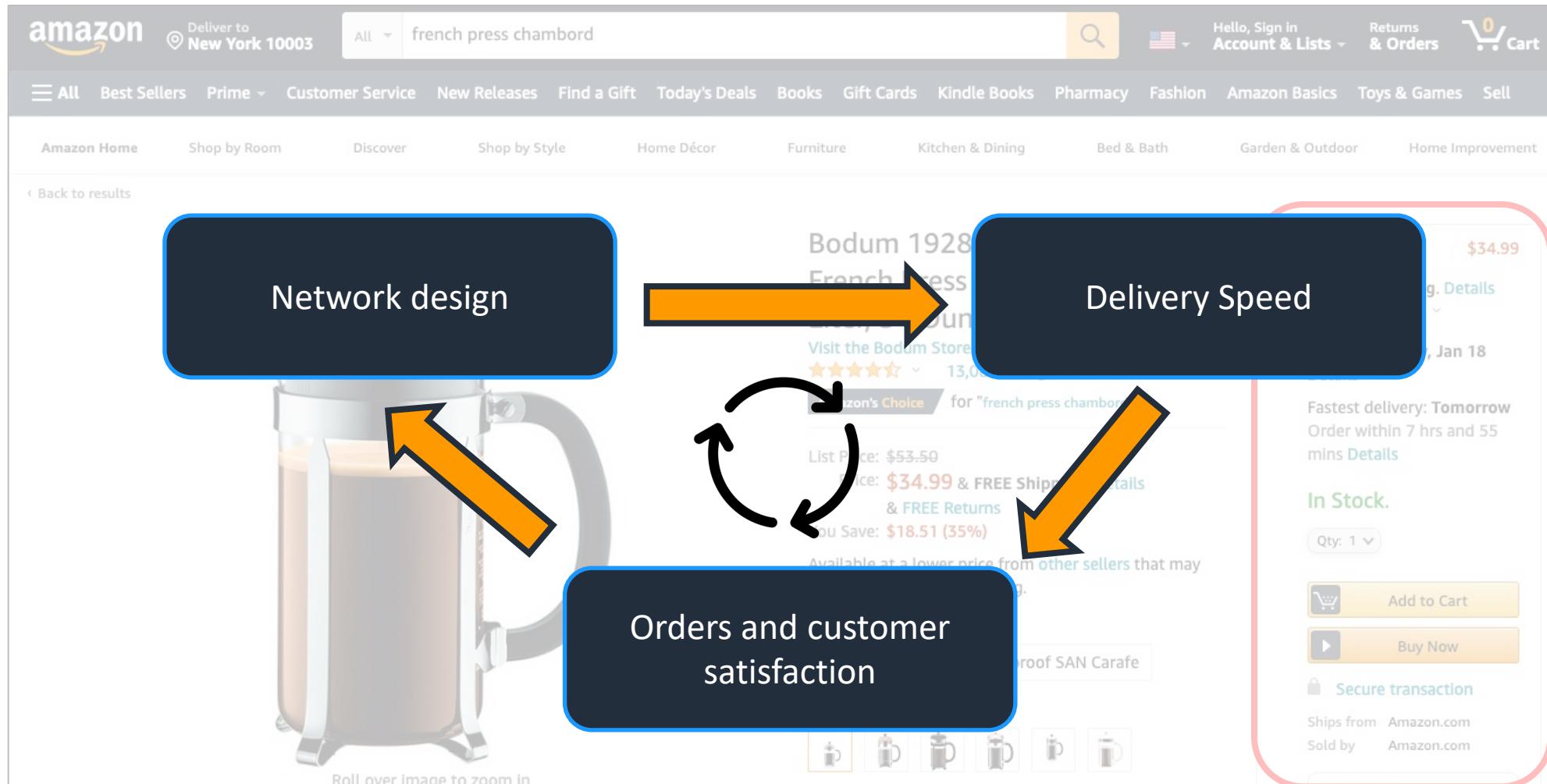
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Why considering speed?



Why considering speed?



Why considering speed?

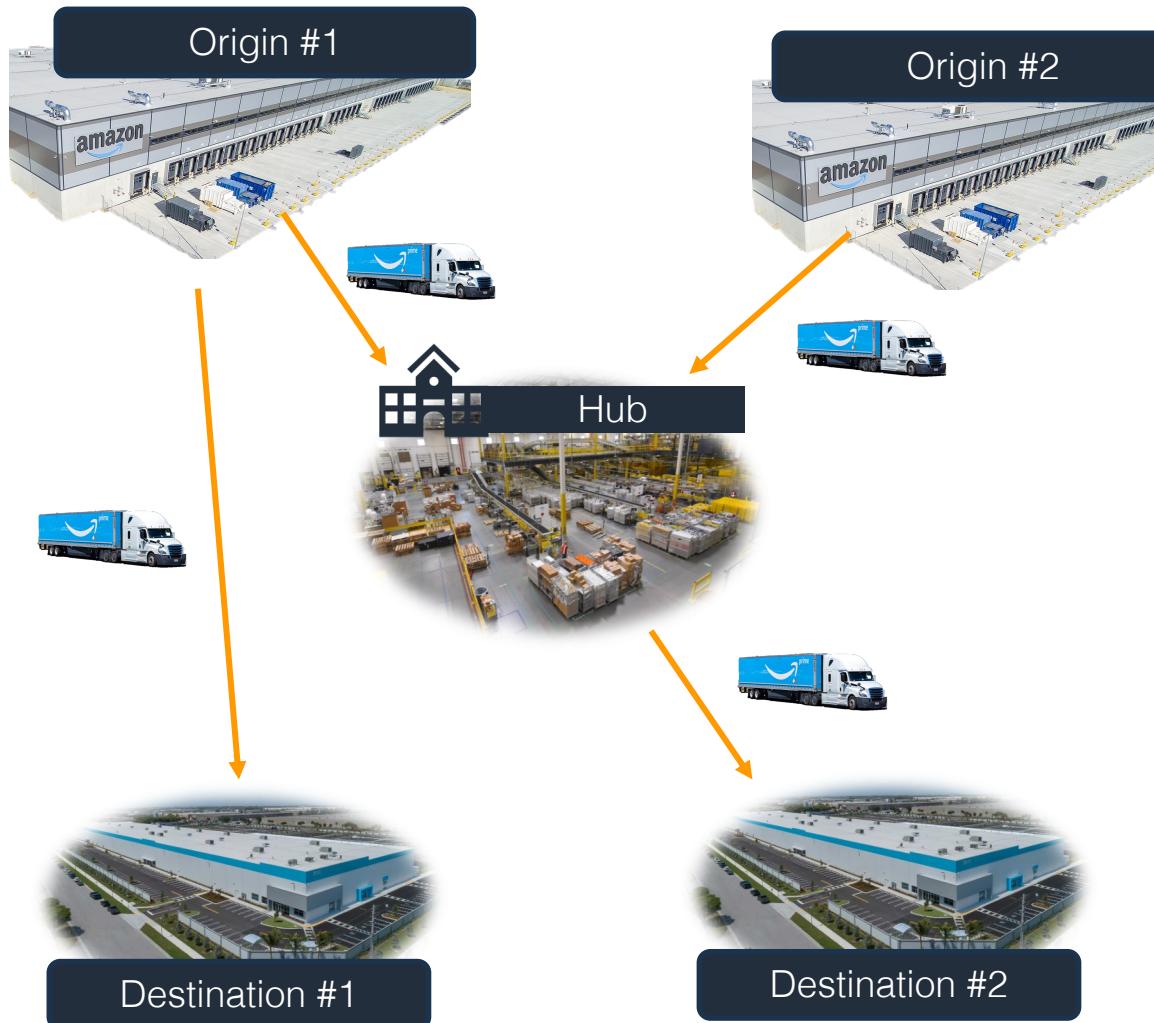
Key objective: Design the cheapest and fastest network for our customers



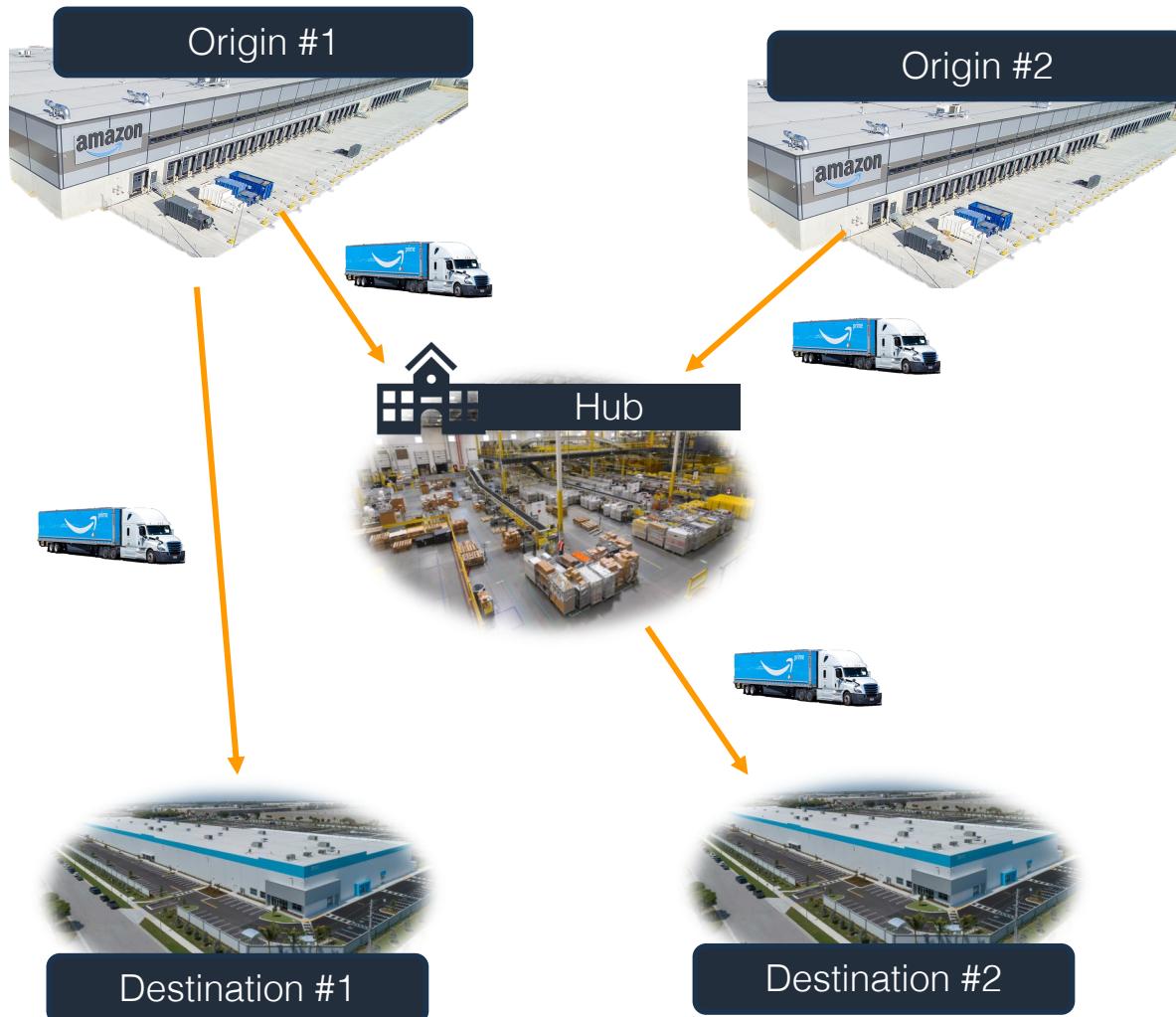
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Network Design: Connectivity

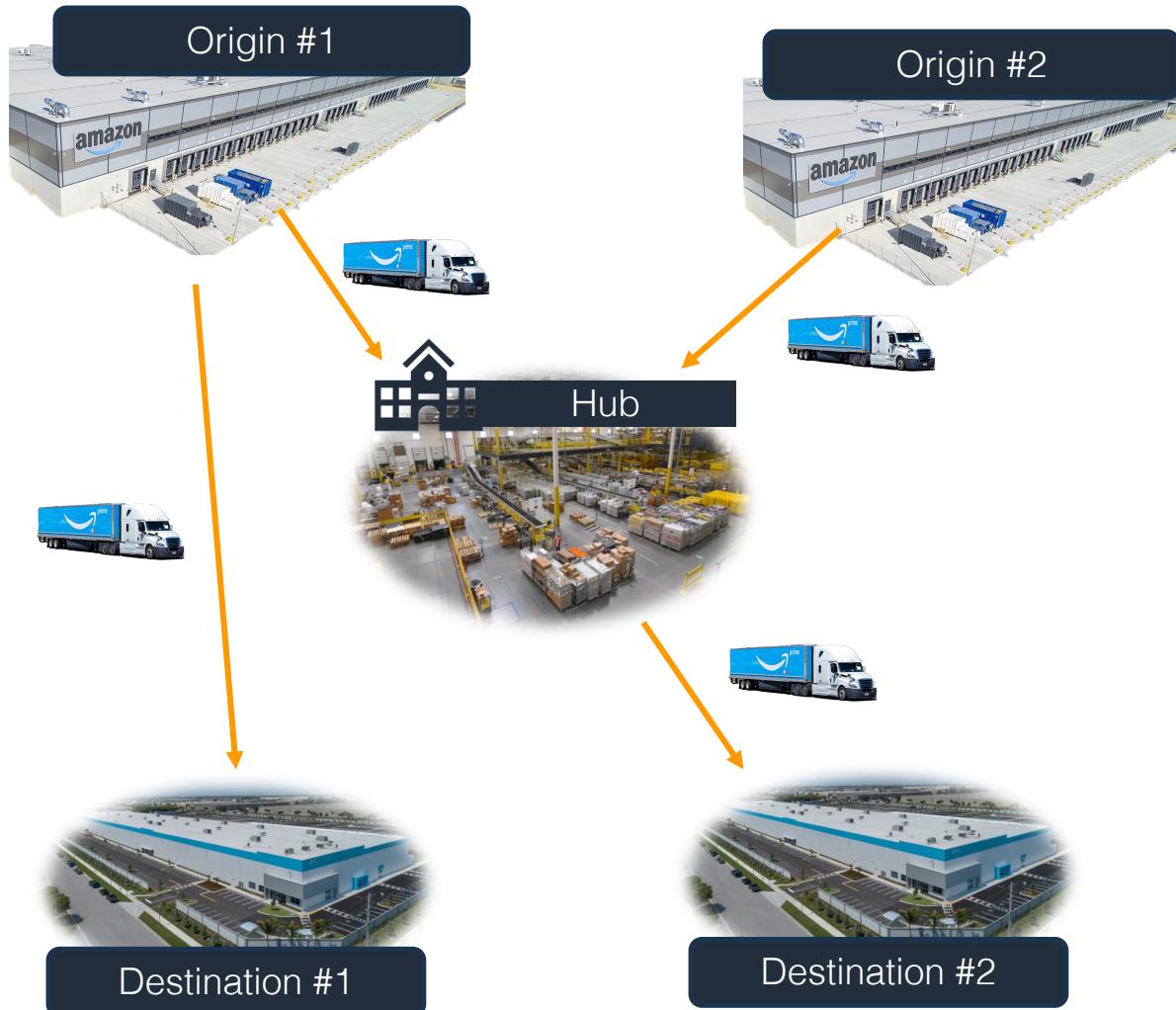


Network Design: Connectivity



$$\begin{aligned} \min_{p,v} \quad & \text{NetworkCost}(p, y) \\ \text{s.t.} \quad & (p, y) \in \text{FeasibleNetwork} \end{aligned}$$

Network Design: Connectivity

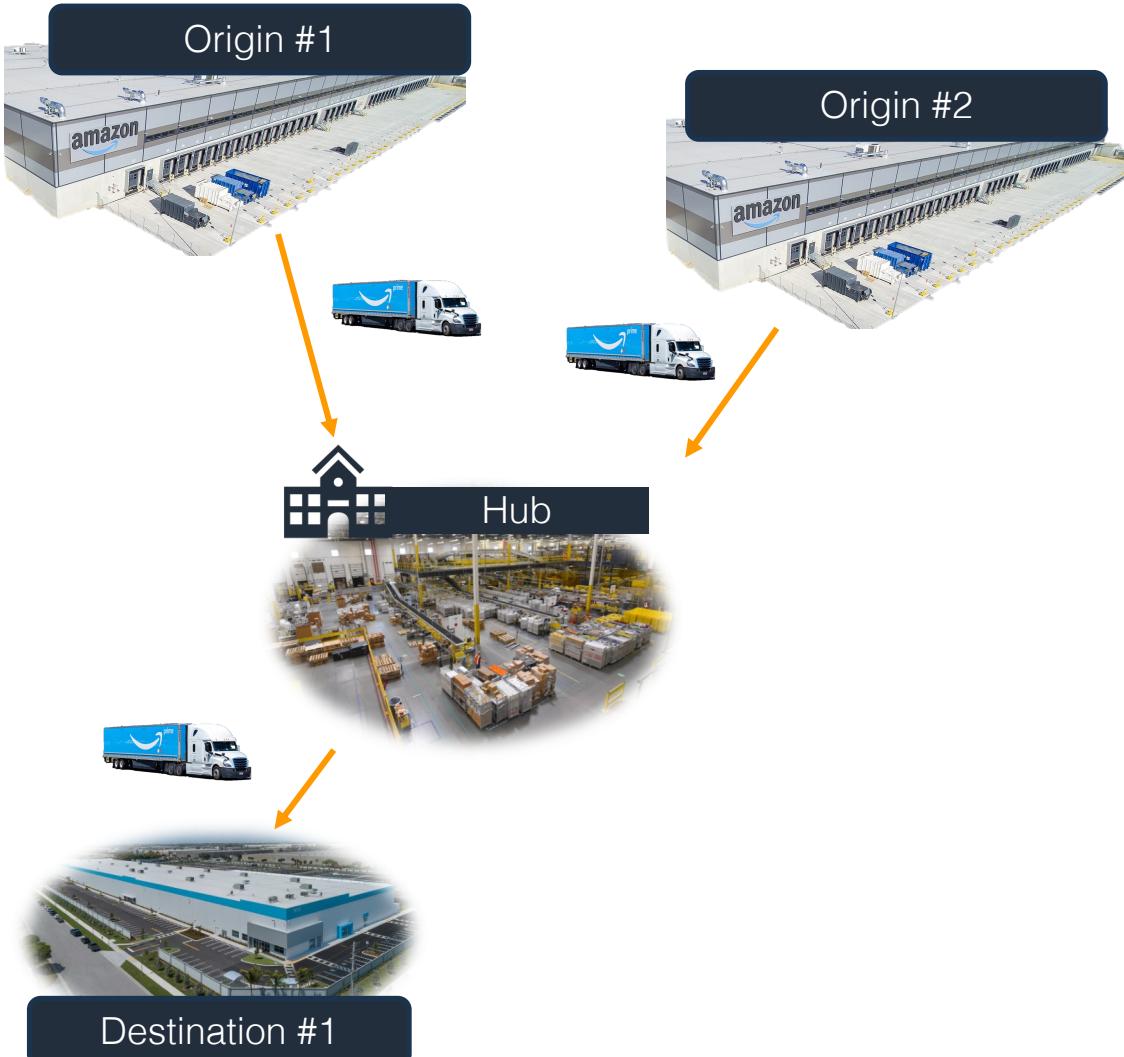


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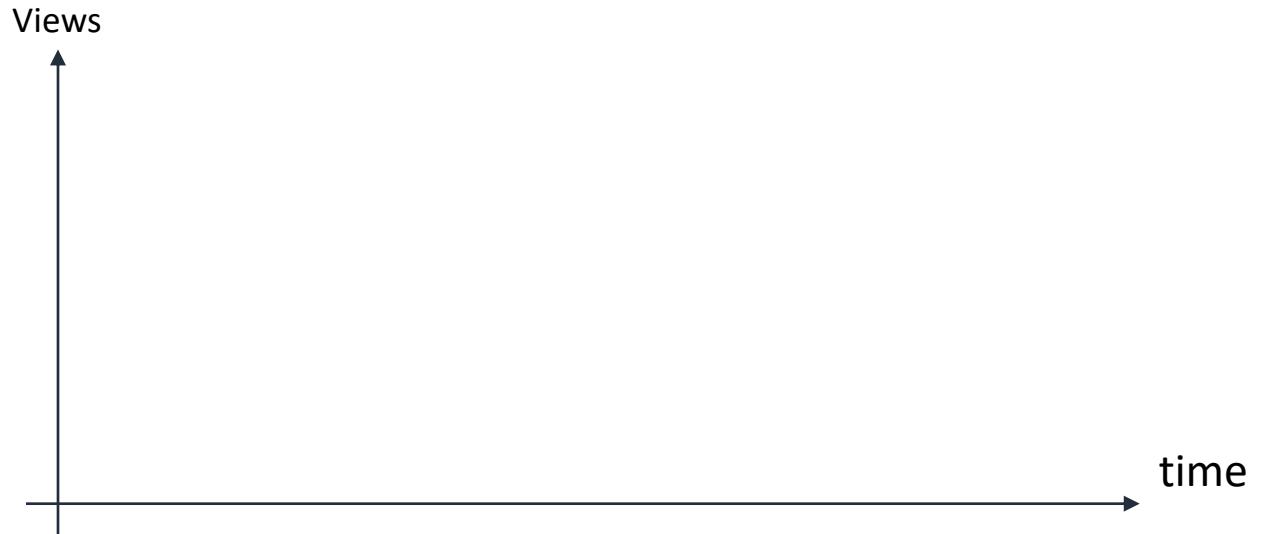
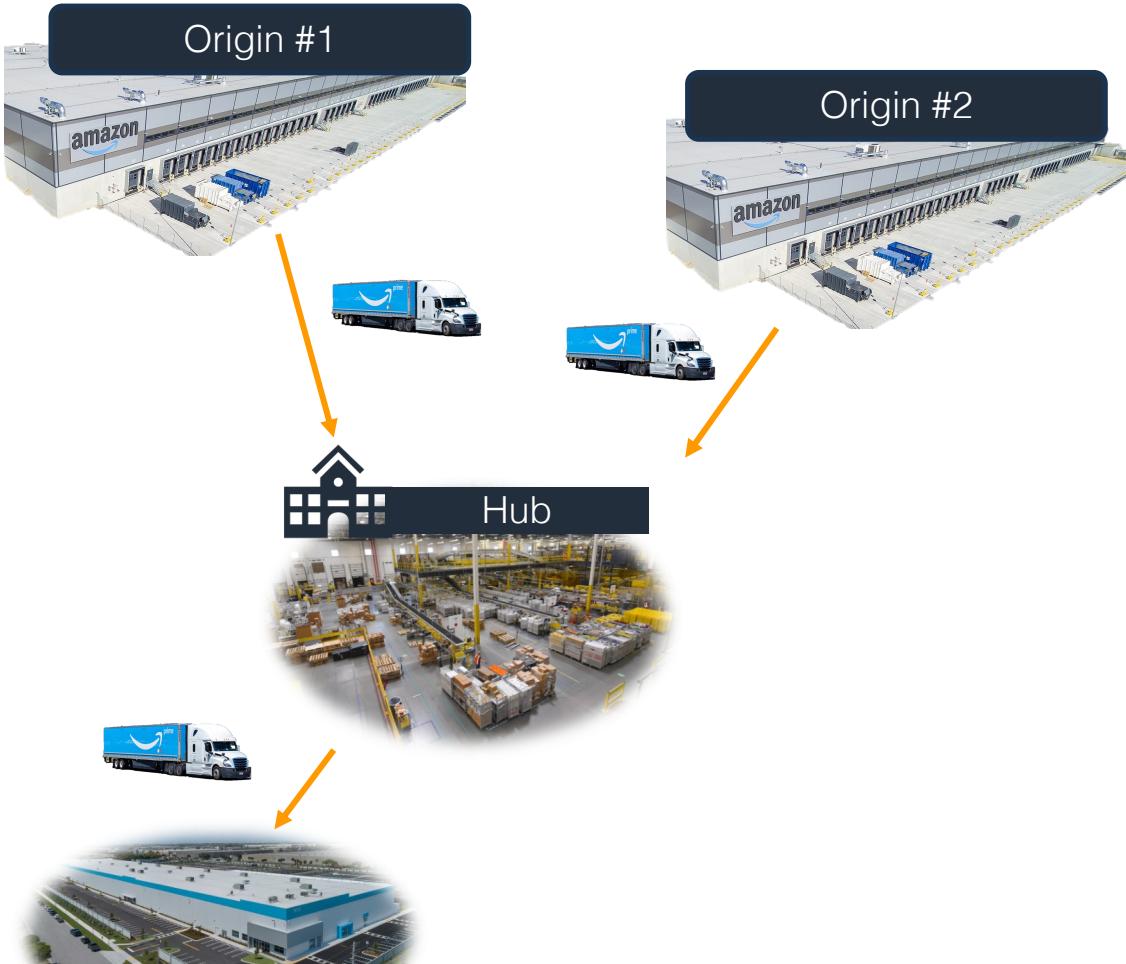
Path vector variable

Trucks vector variable

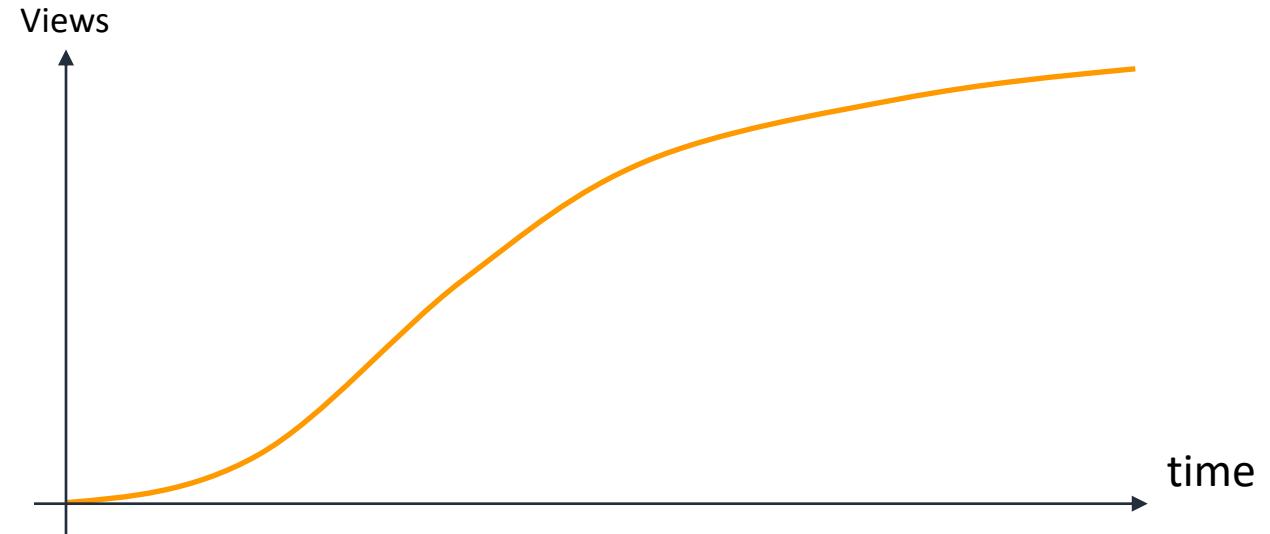
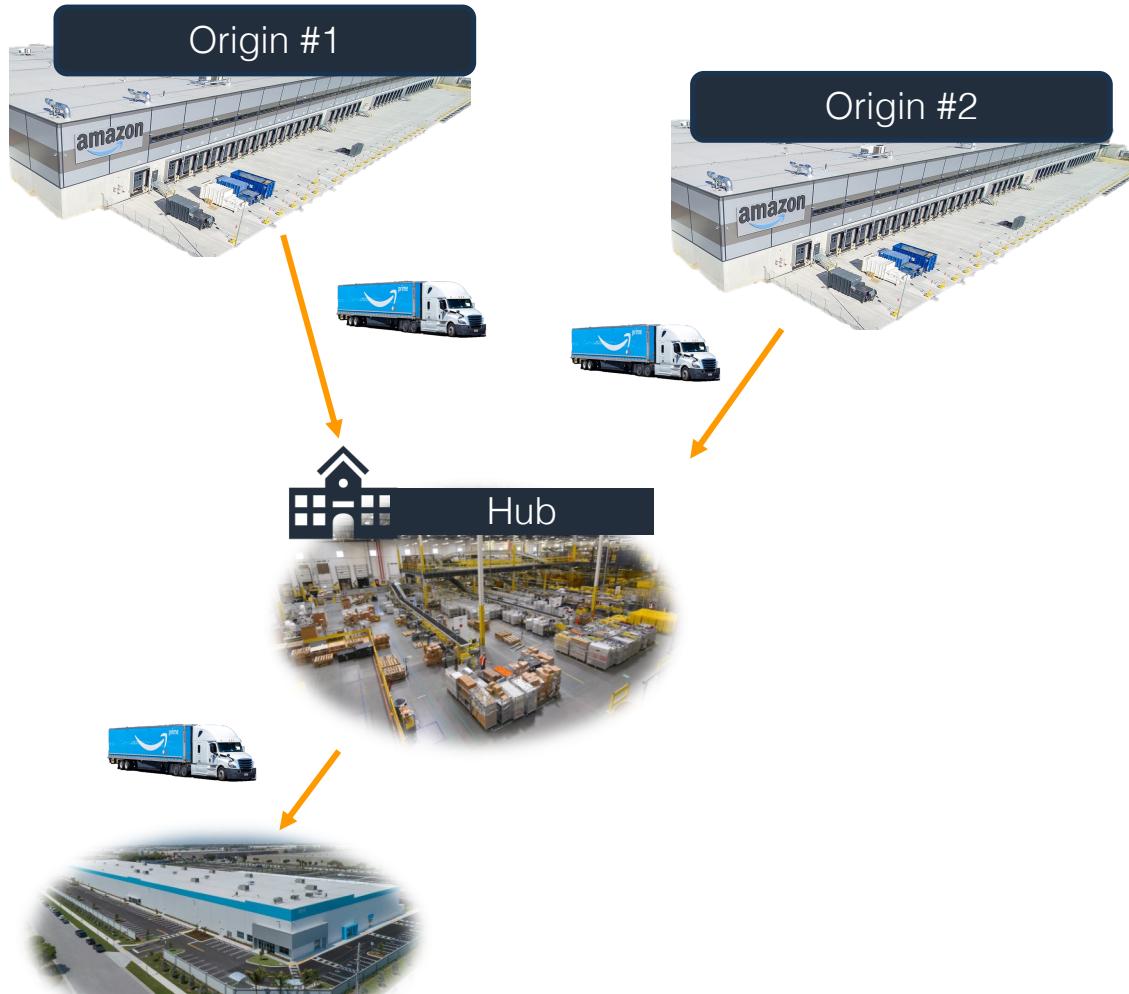
Network Design: Timing



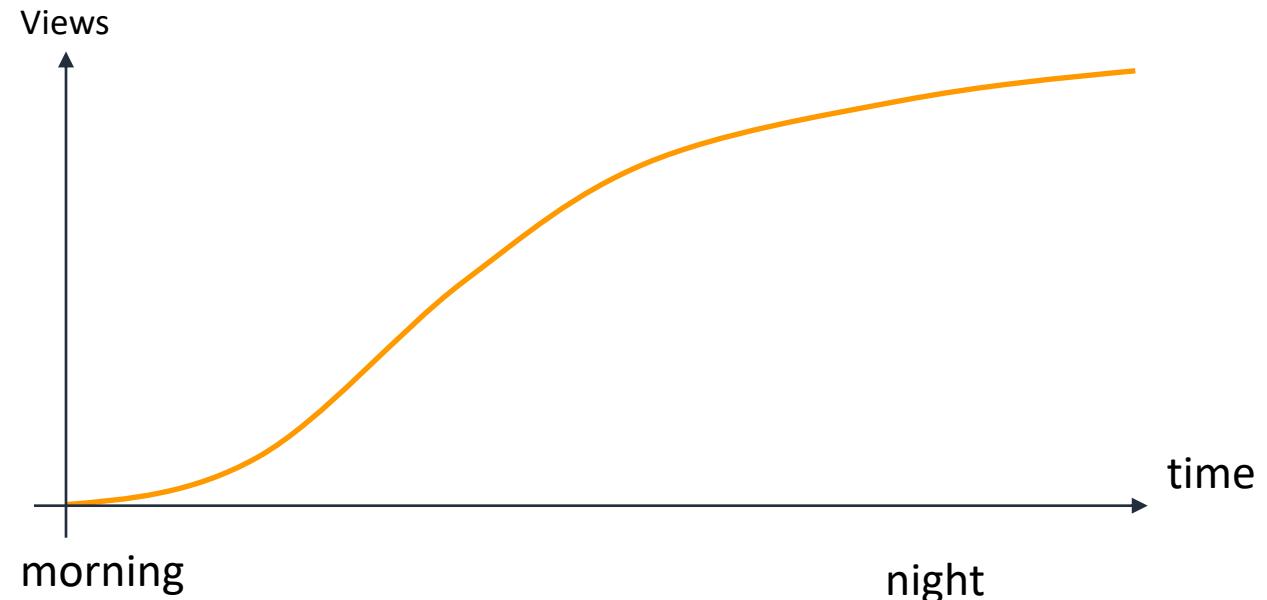
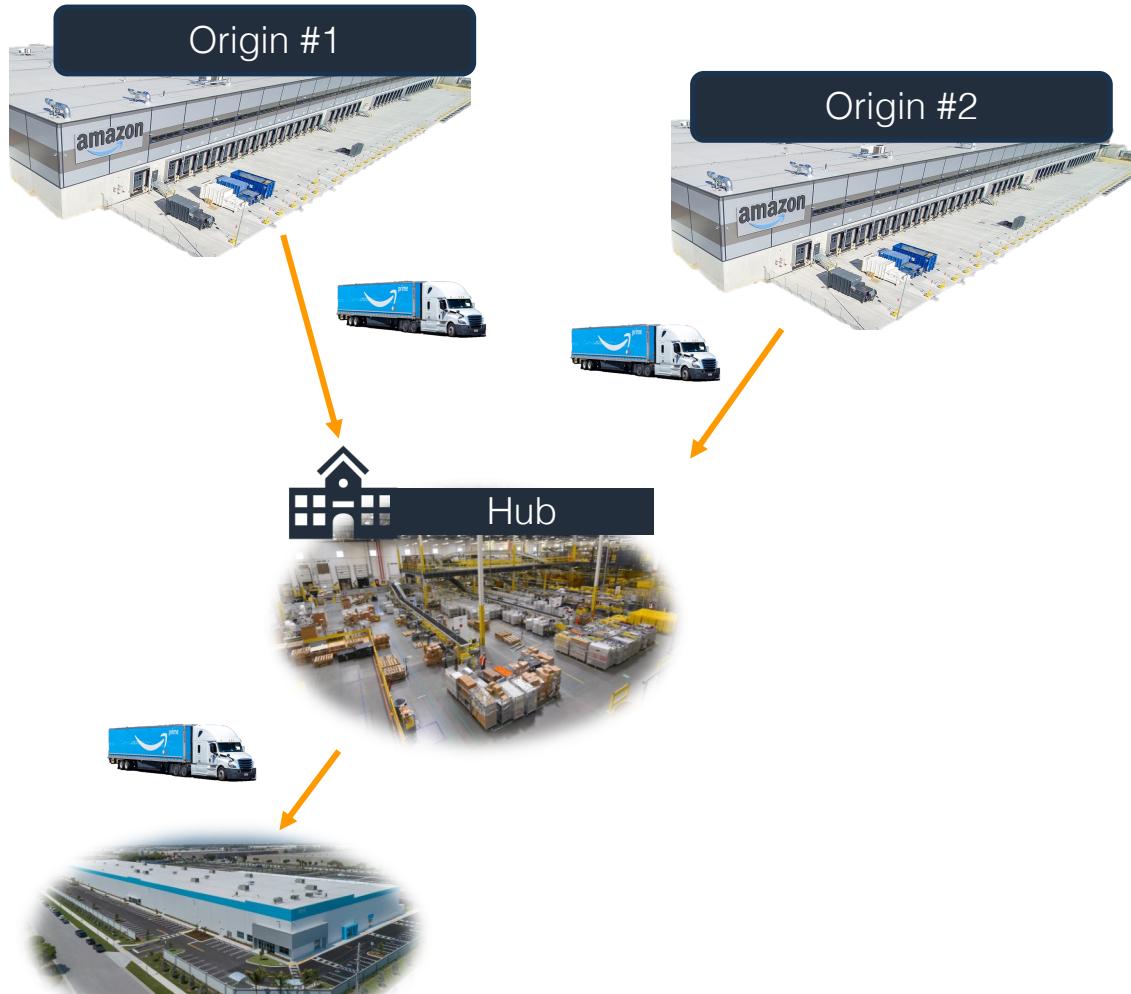
Network Design: Timing



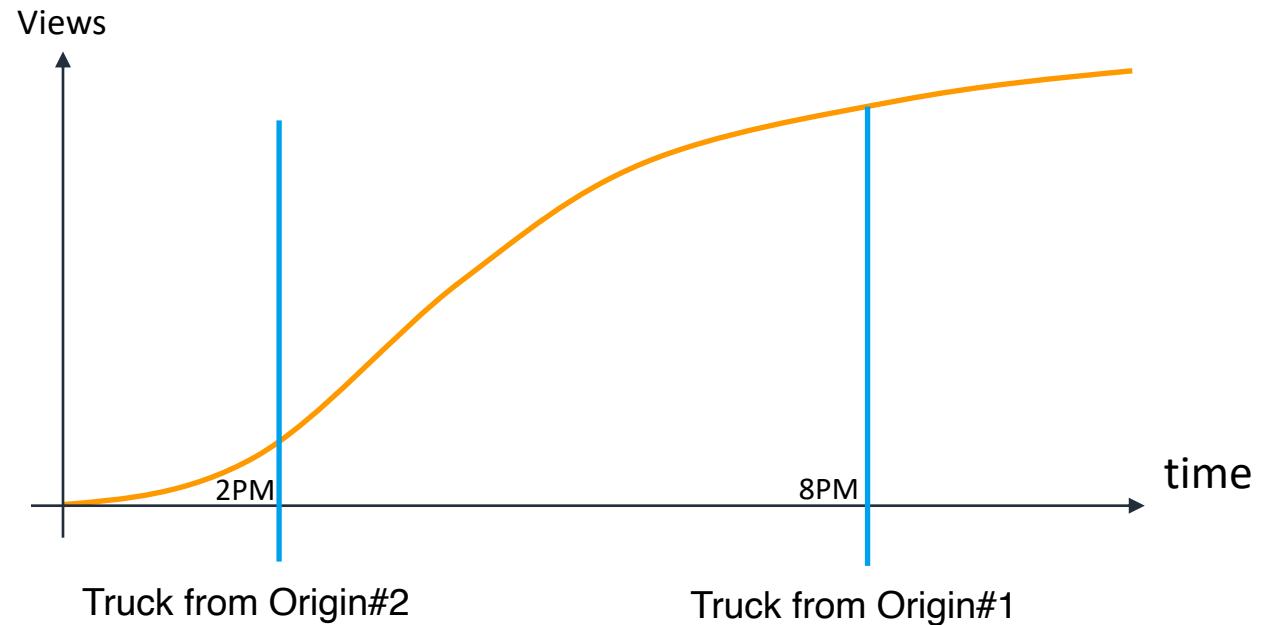
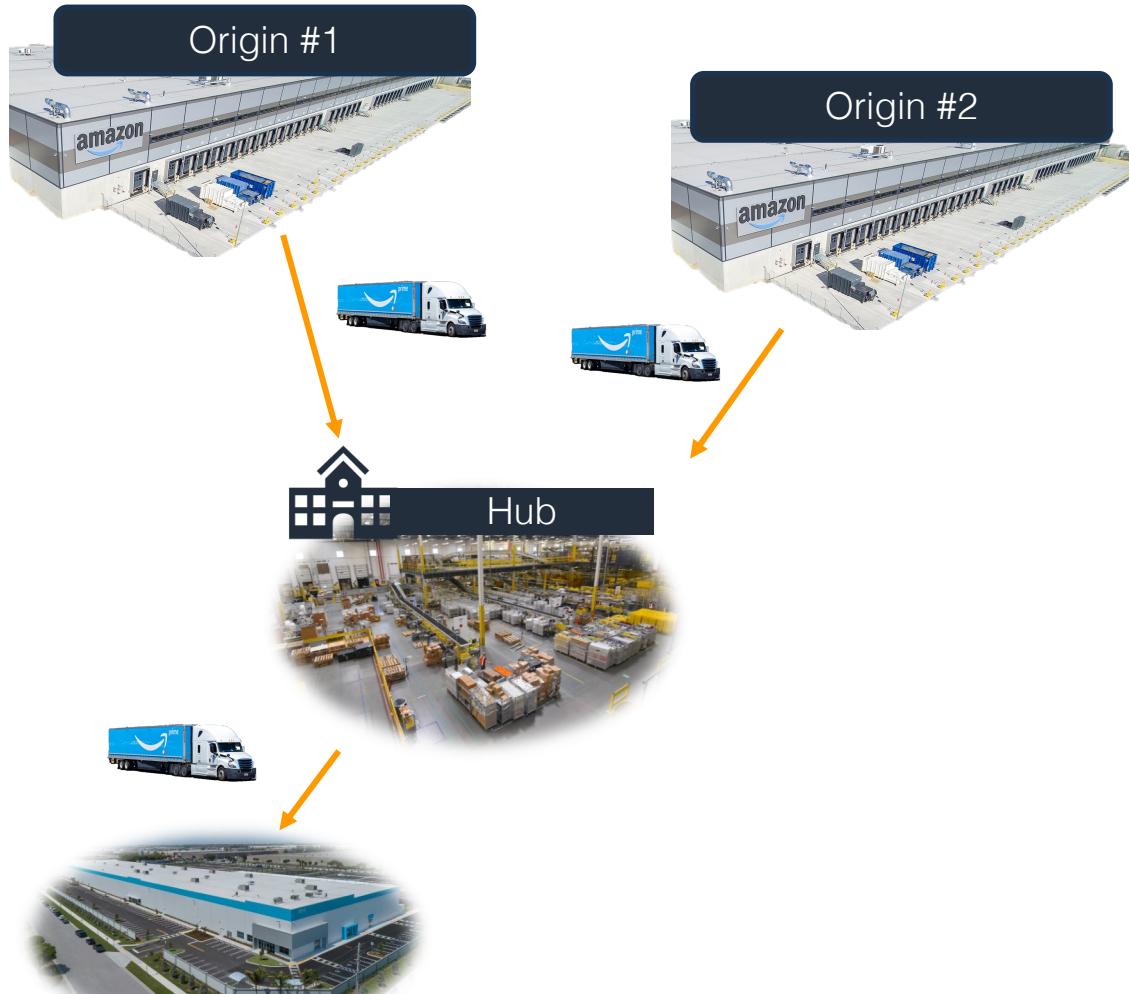
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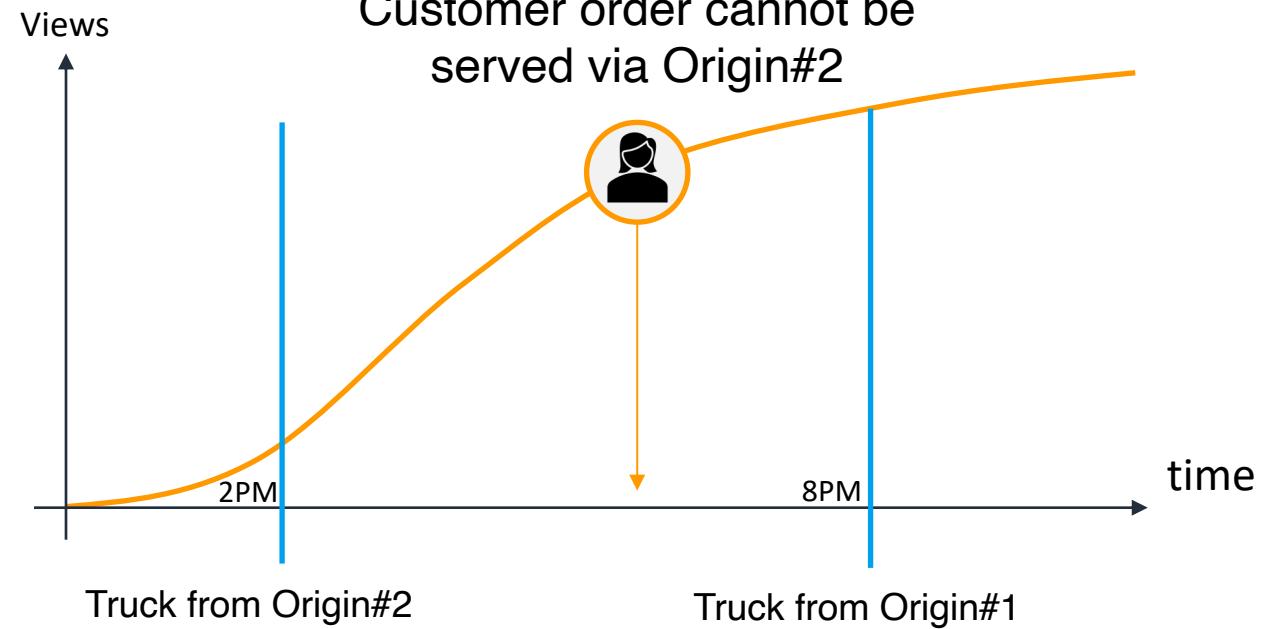
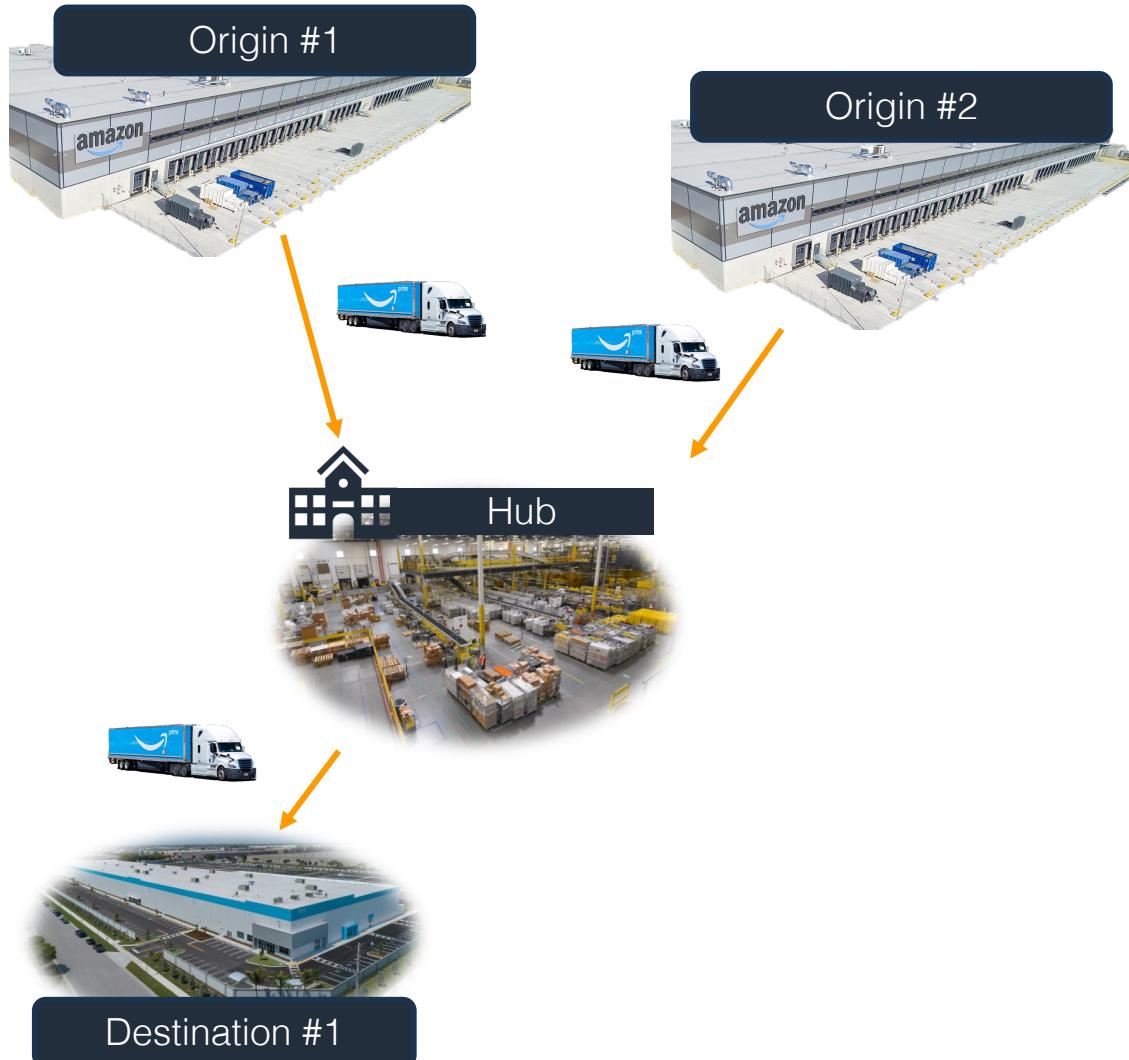
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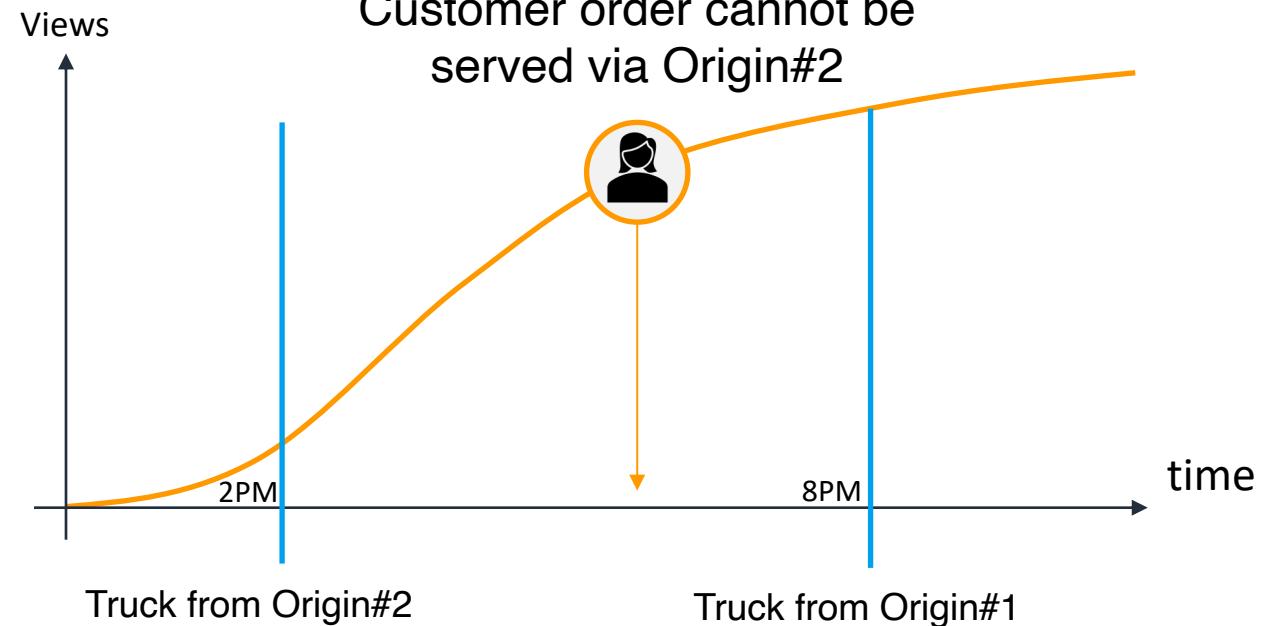
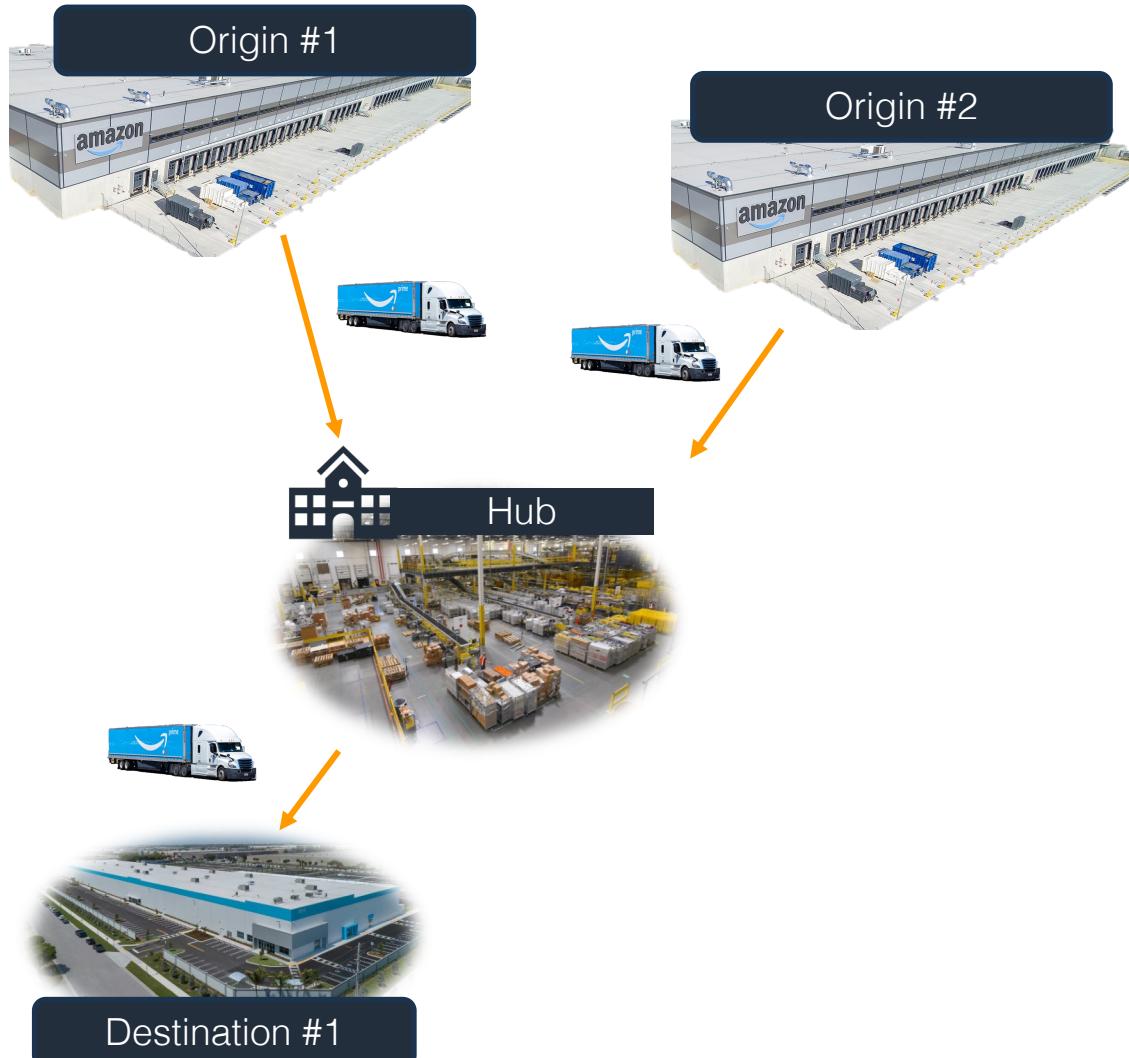
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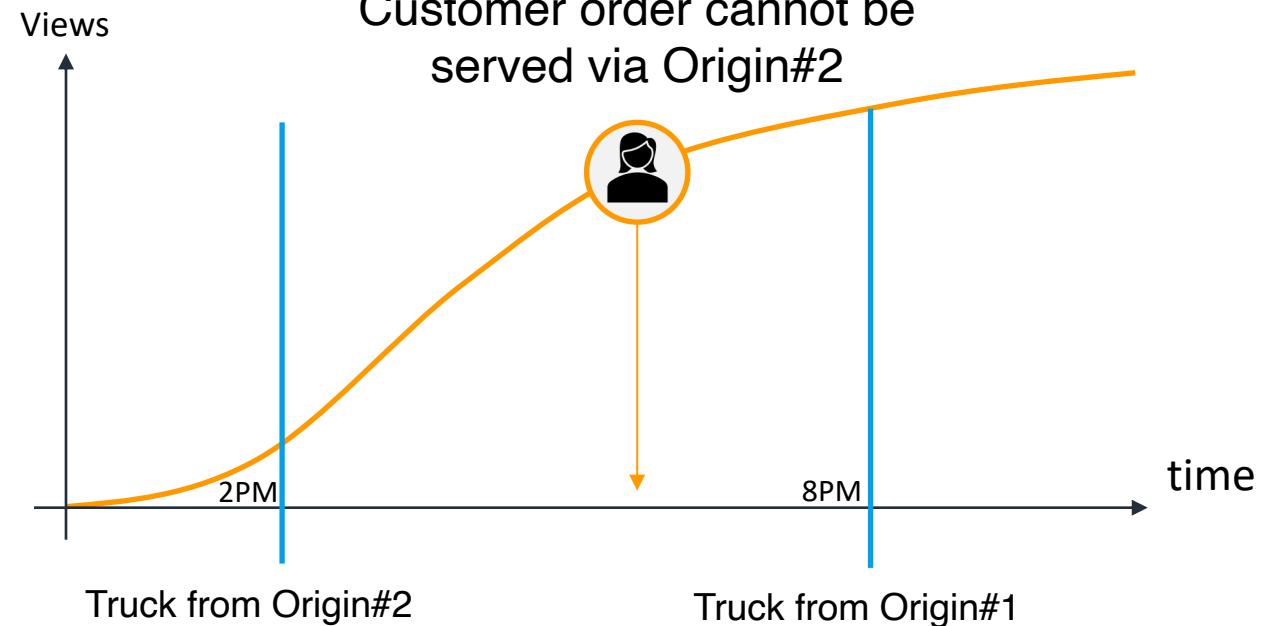
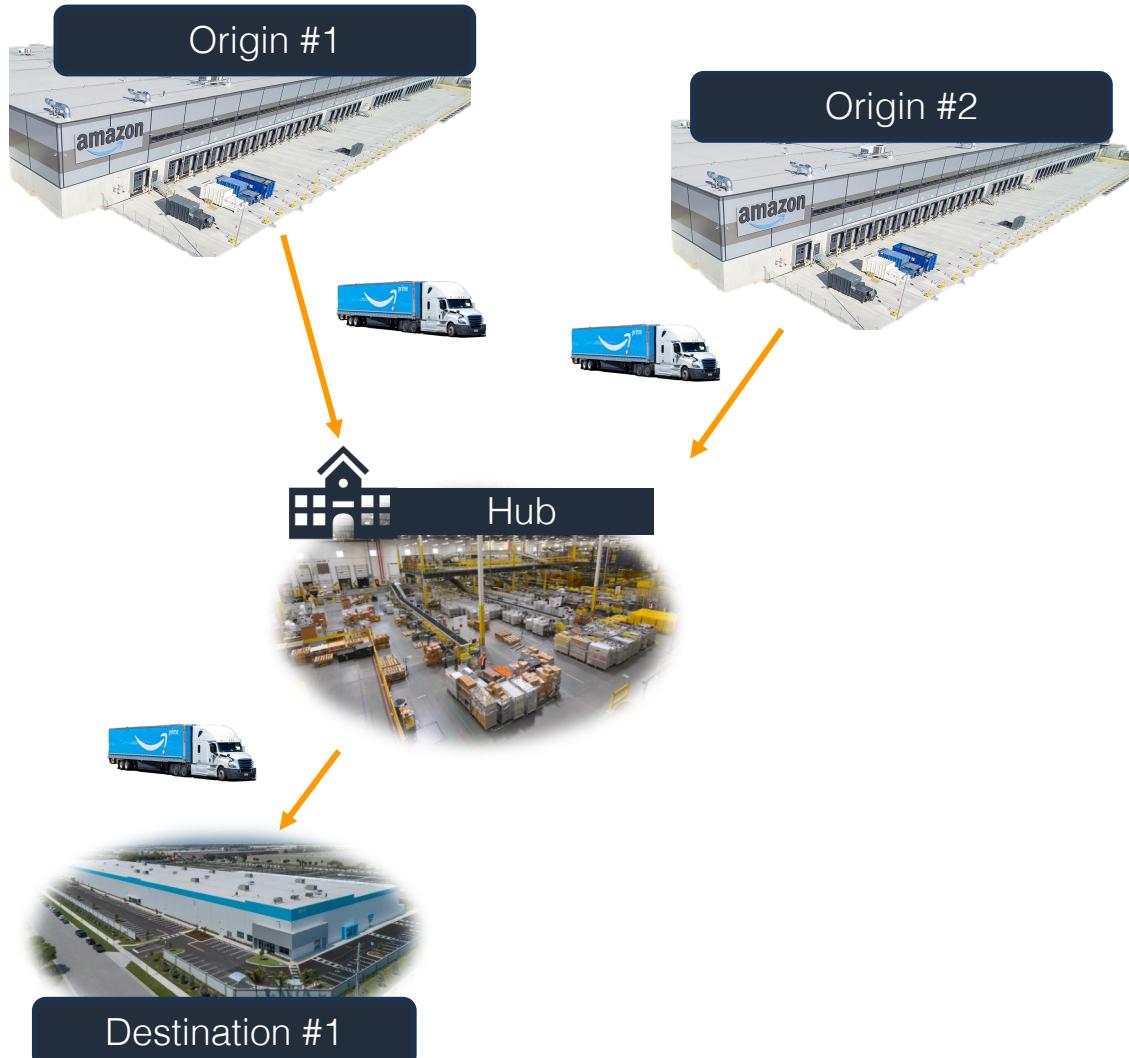


Network Design: Timing



$$\begin{aligned} & \max_z \quad \text{Speed}(z) \\ \text{s.t.} \quad & z \in \text{FeasibleSchedule}(p) \end{aligned}$$

Network Design: Timing


$$\max_z$$
$$\text{Speed}(z)$$

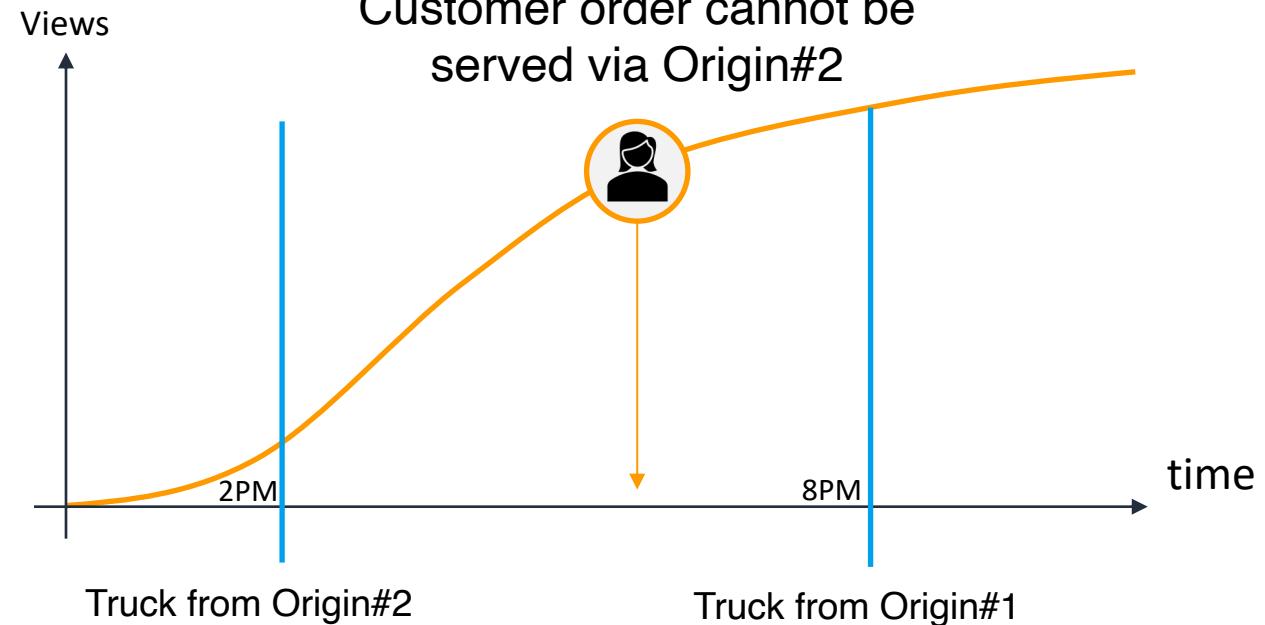
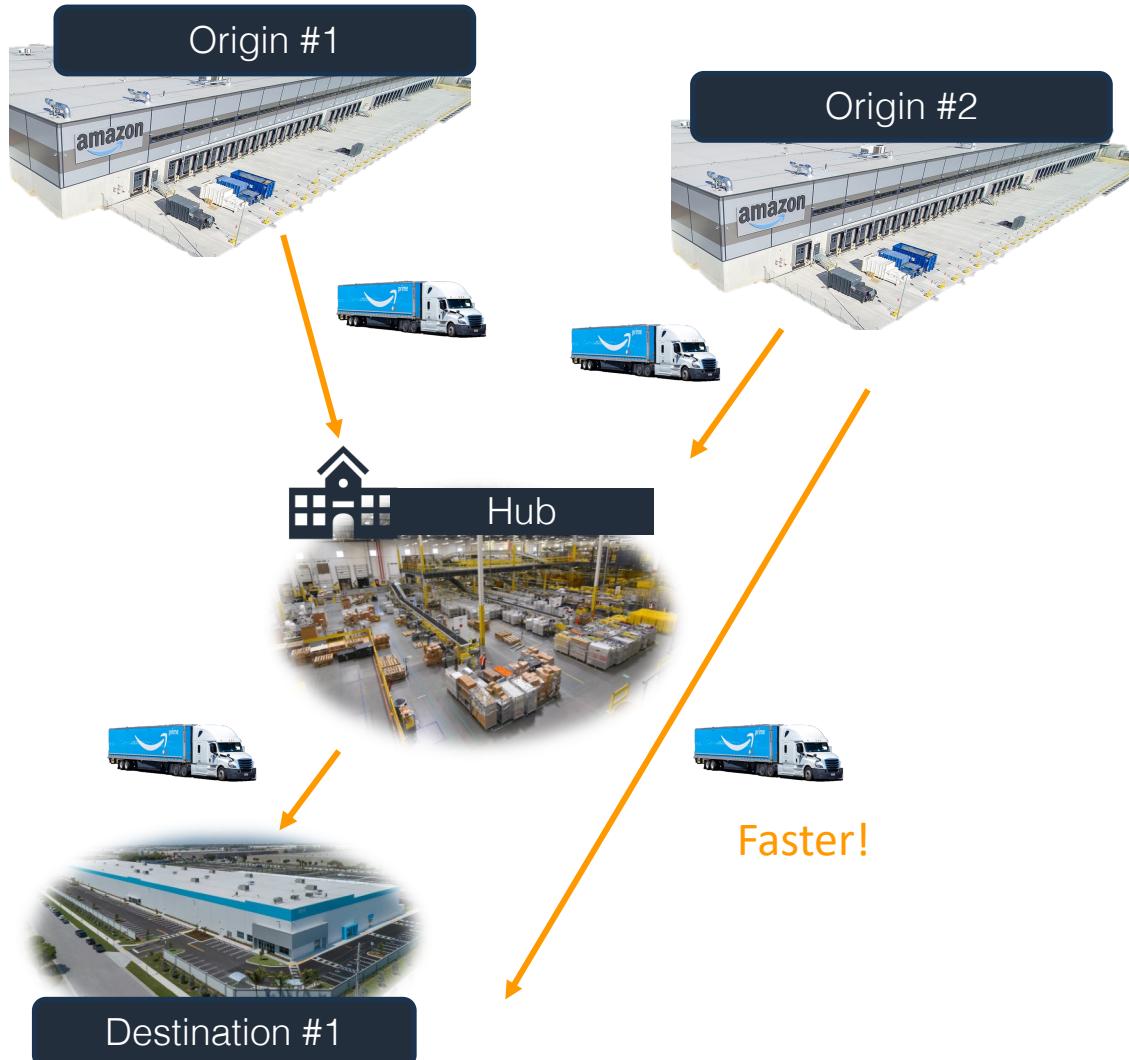
s.t.

$$z \in \text{FeasibleSchedule}(p)$$

Truck schedule vector variable

Dependency on connectivity

Network Design: Timing



$$\max_z \text{Speed}(z)$$

$$\text{s.t. } z \in \text{FeasibleSchedule}(p)$$

Truck schedule vector variable

Dependency on connectivity

Network Design: The joint problem

$$\begin{aligned} \min_{p, y, z} \quad & \text{NetworkCost}(p, y) - \text{Speed}(z) \\ \text{s.t.} \quad & (p, y) \in \text{FeasibleNetwork} \\ & z \in \text{FeasibleSchedule}(p) \end{aligned}$$

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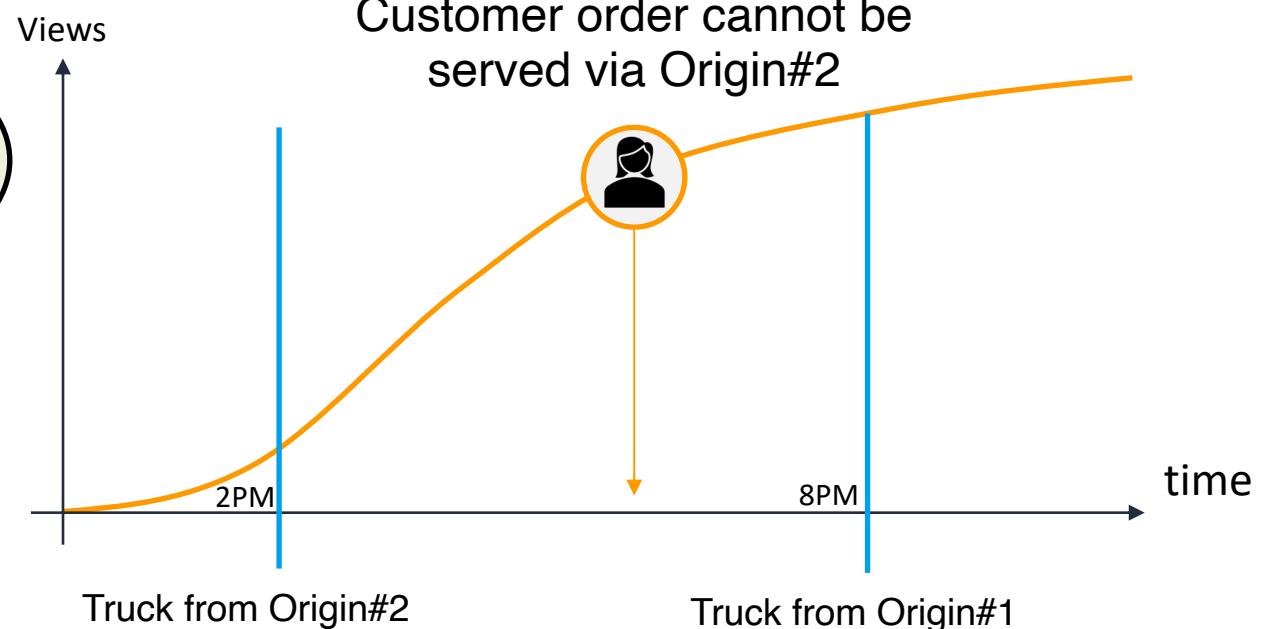
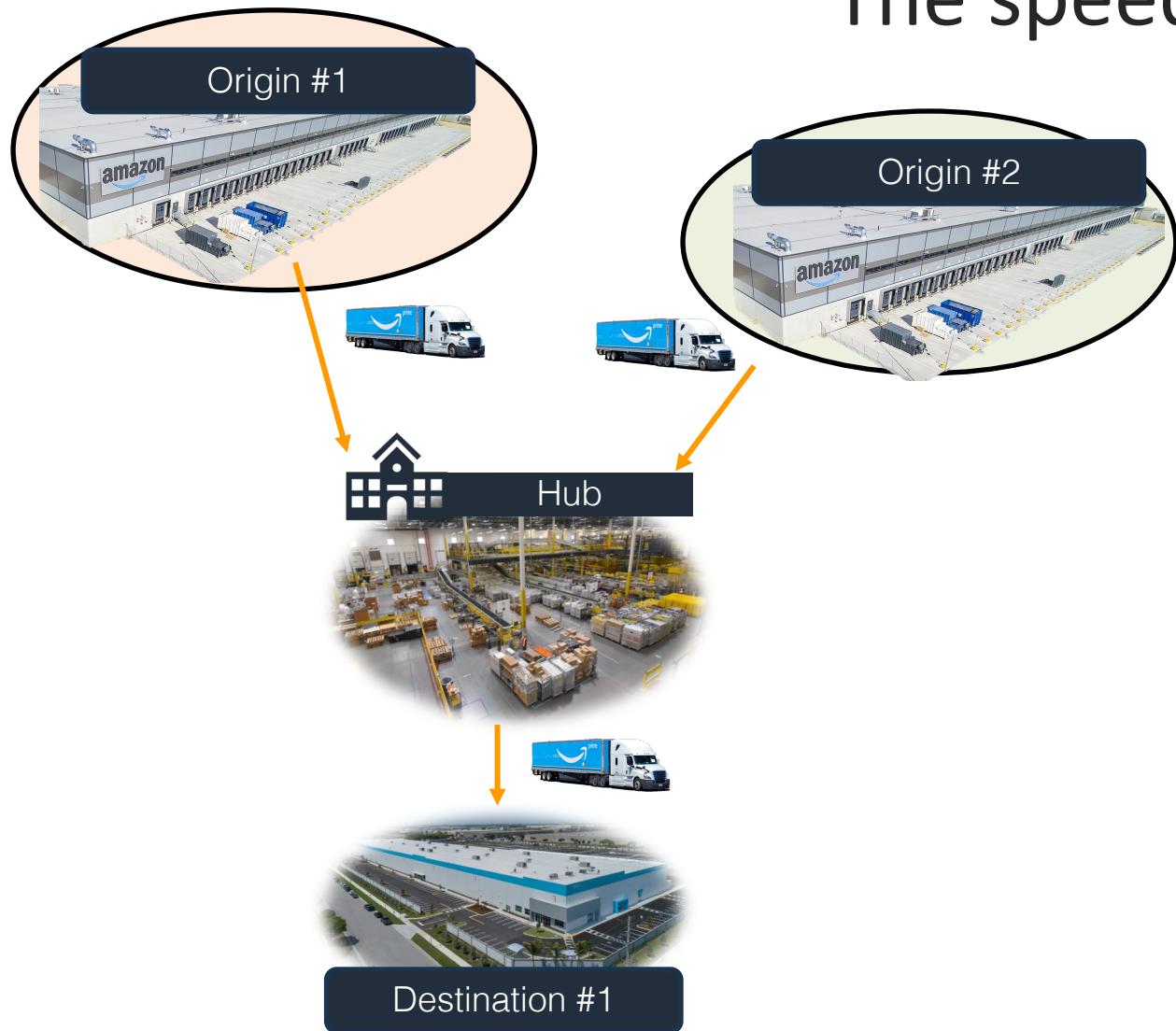
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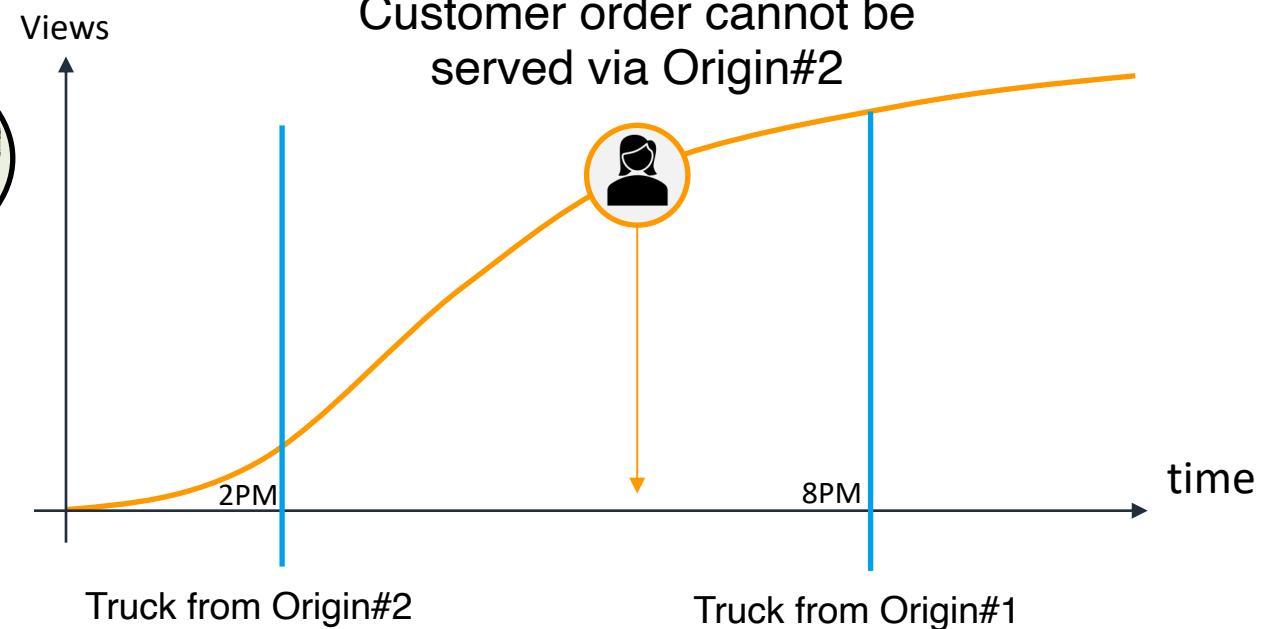
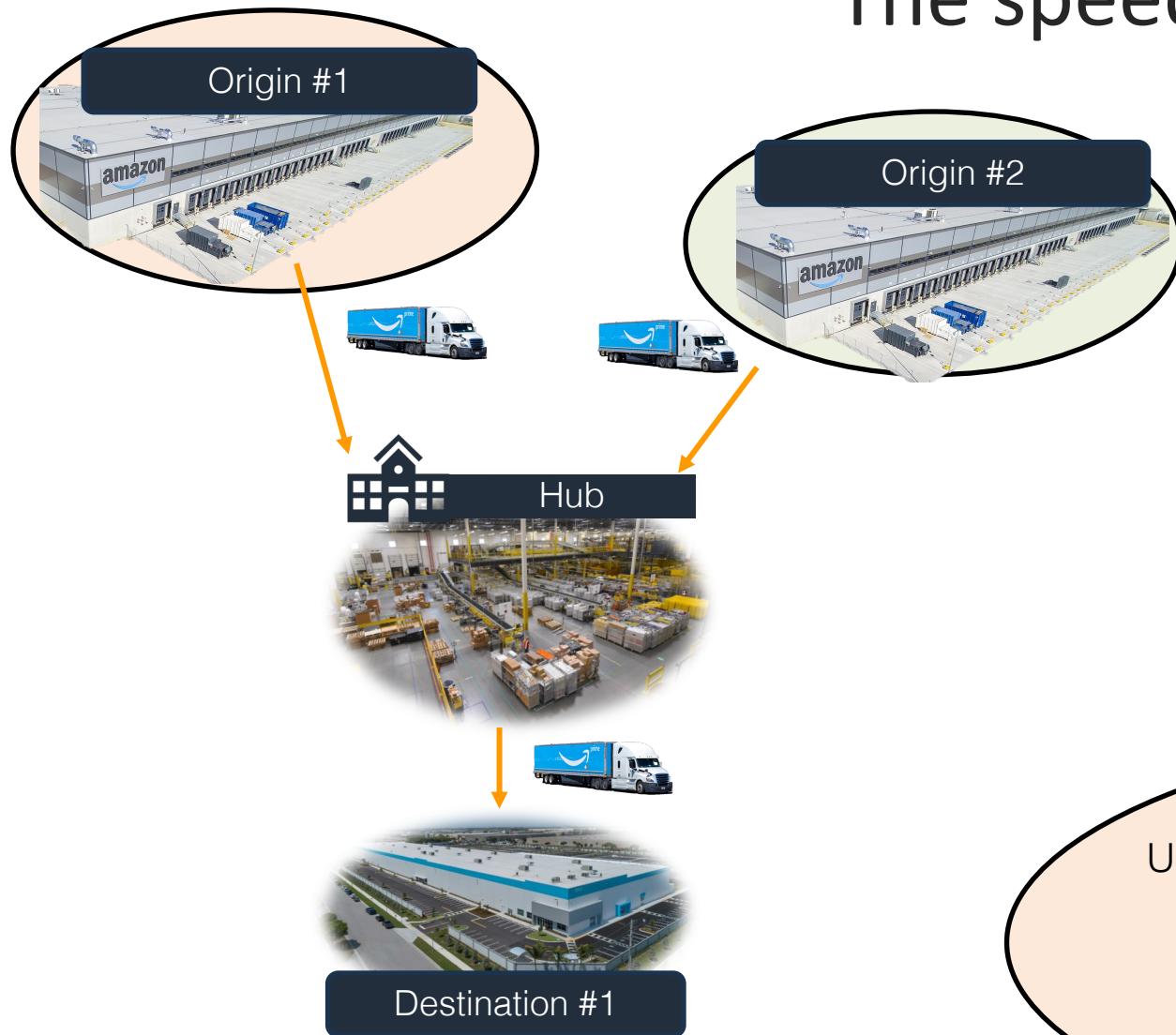
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The speed objective



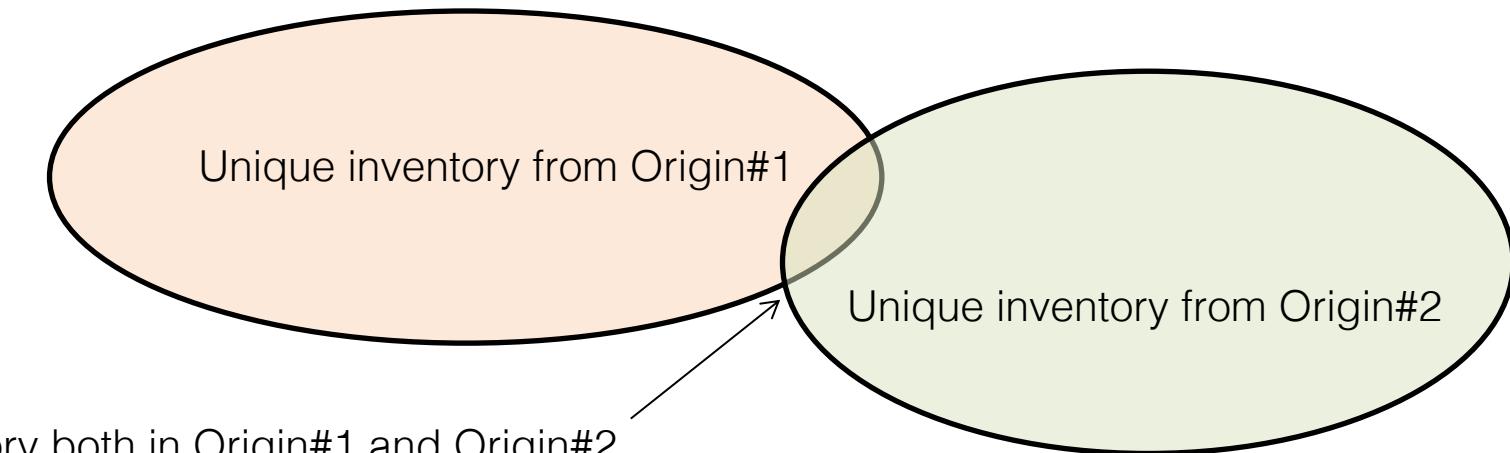
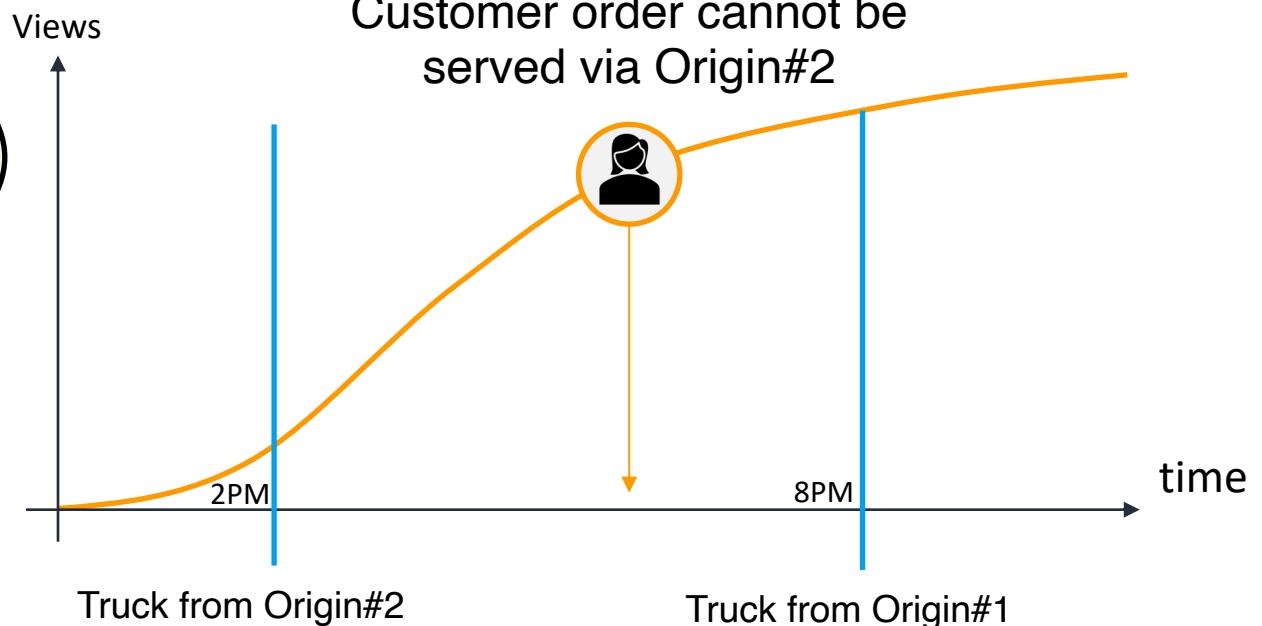
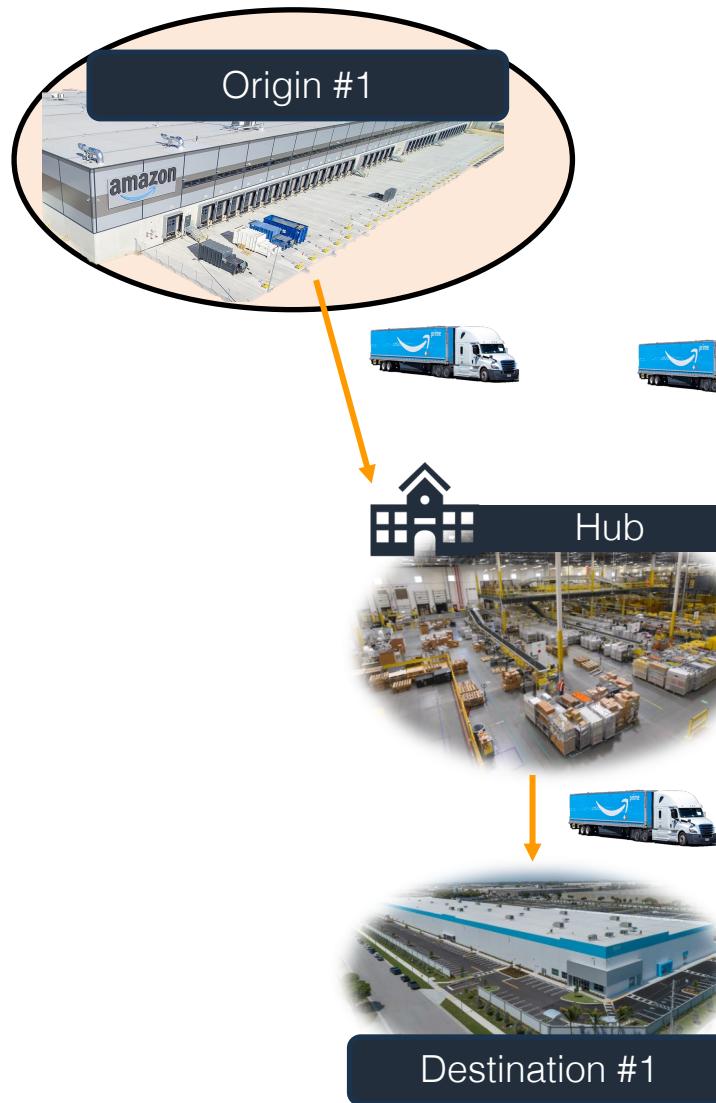
The speed objective



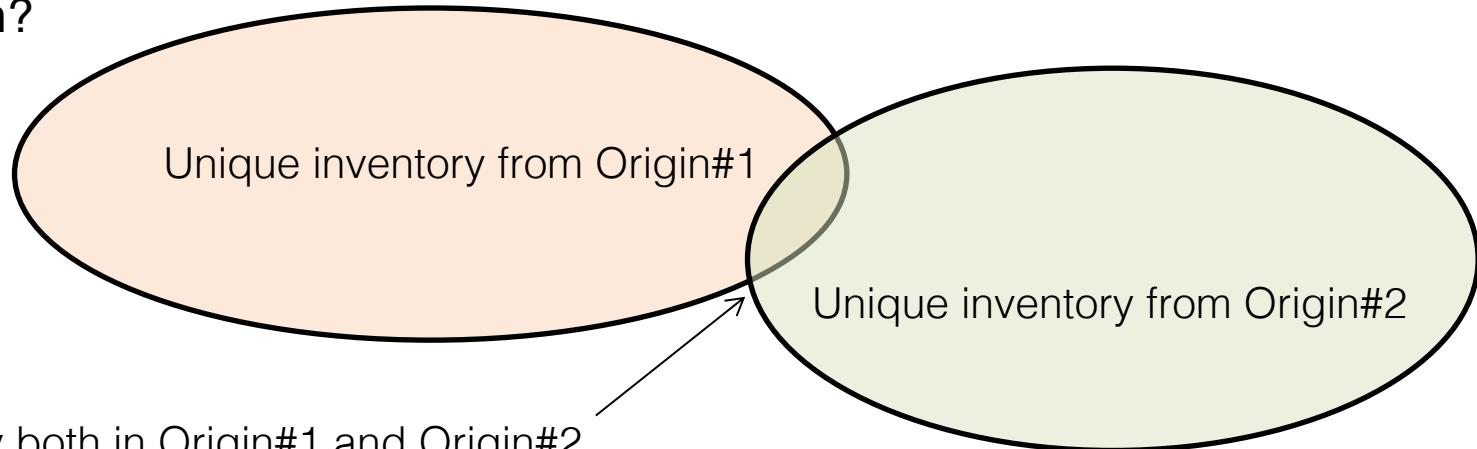
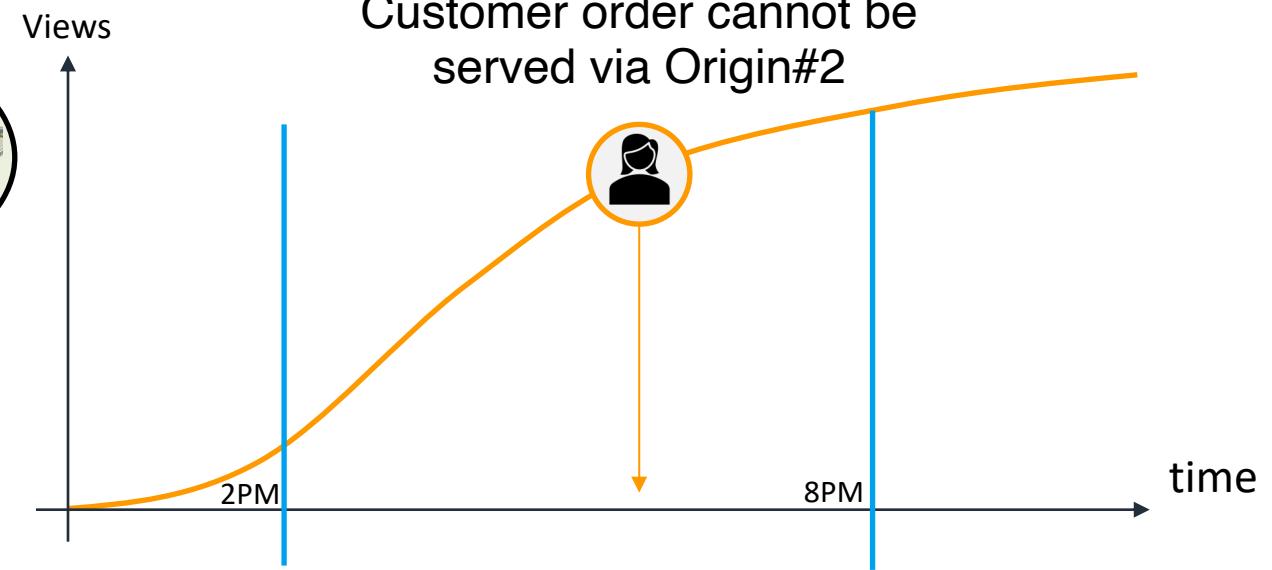
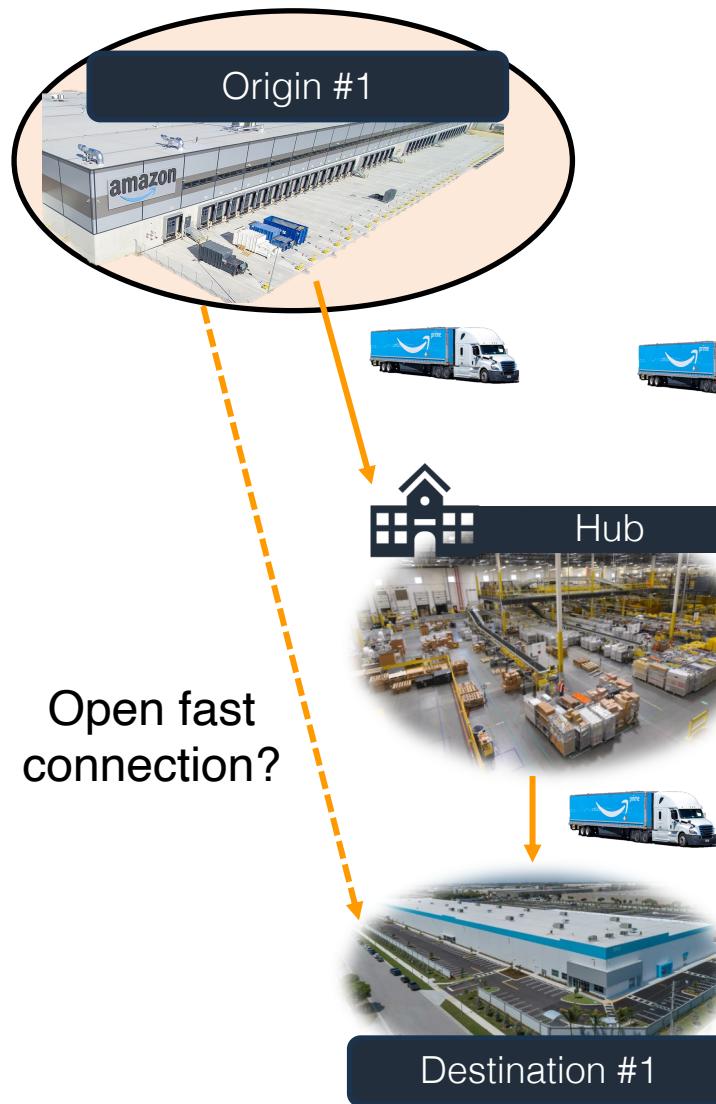
Unique inventory from Origin#1

Unique inventory from Origin#2

The speed objective

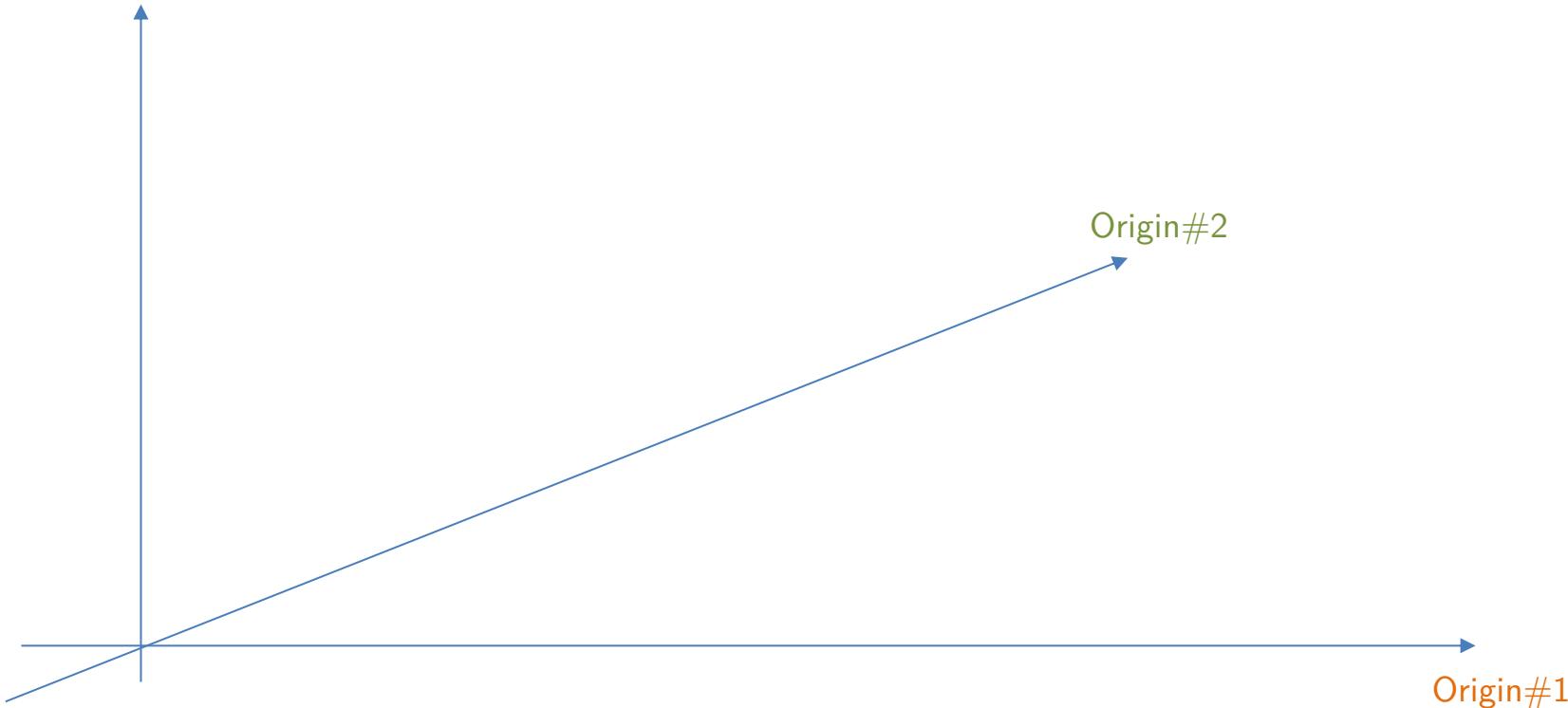


The speed objective



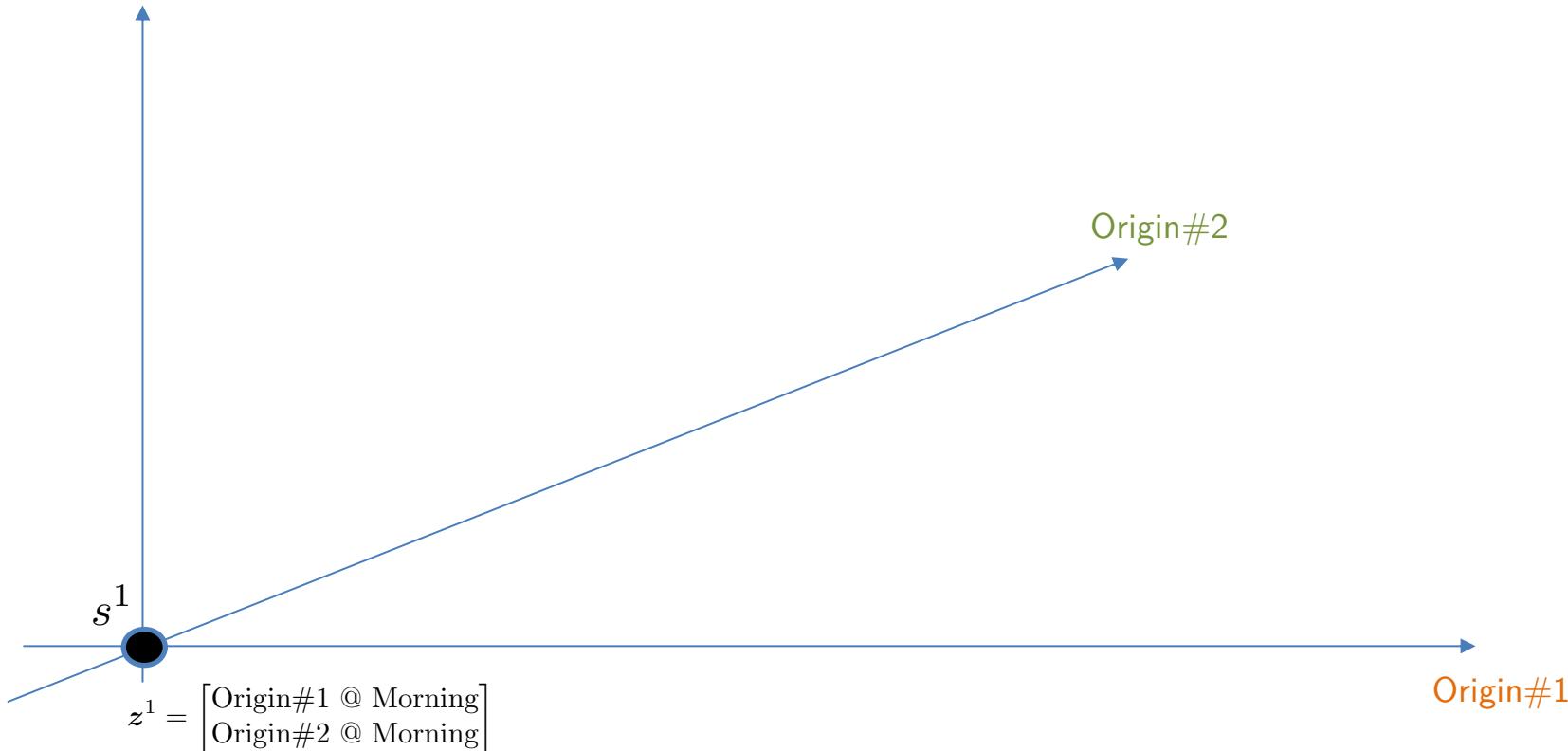
The speed objective

$\text{Speed}(z)$ = unique items that can be delivered in 1-day



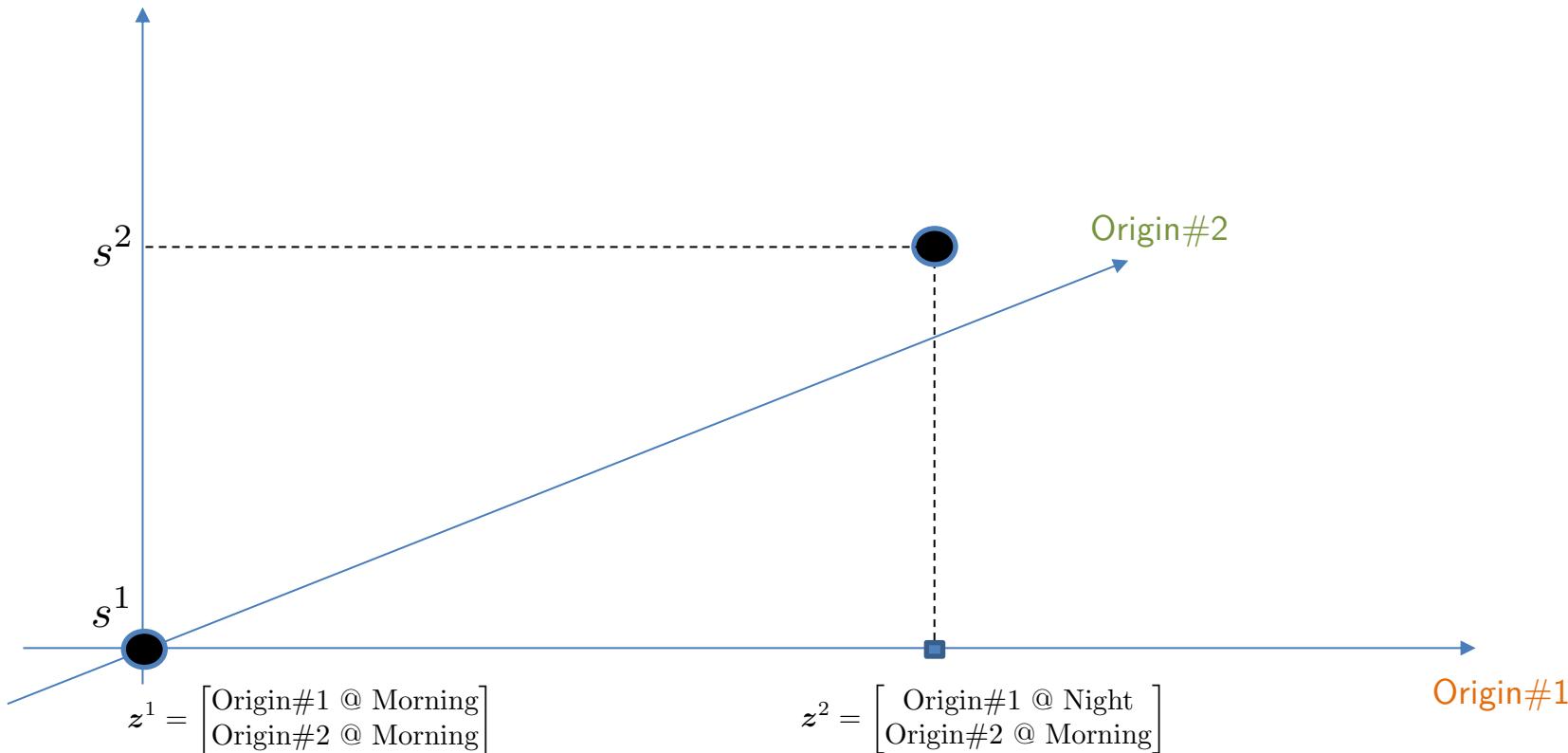
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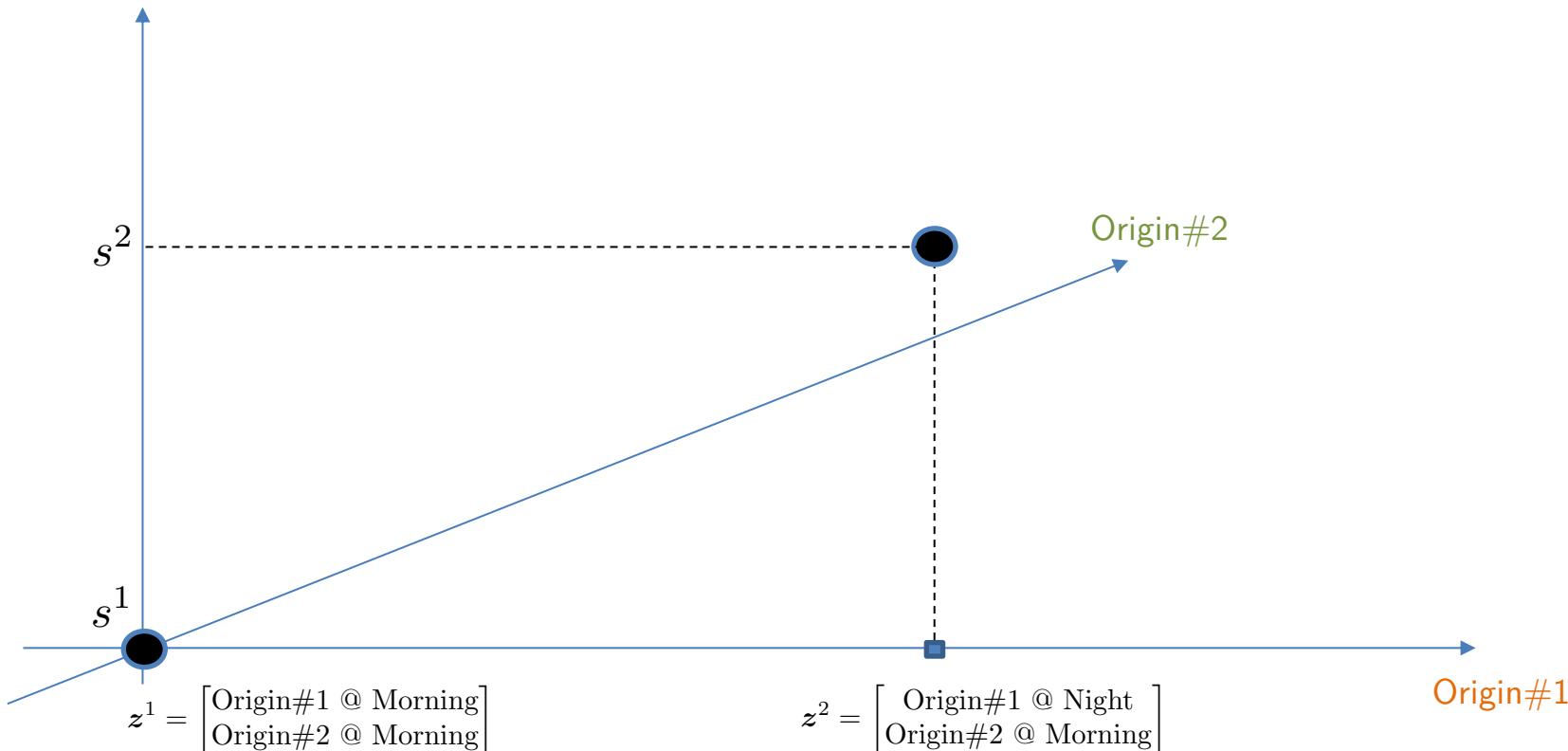
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The speed objective

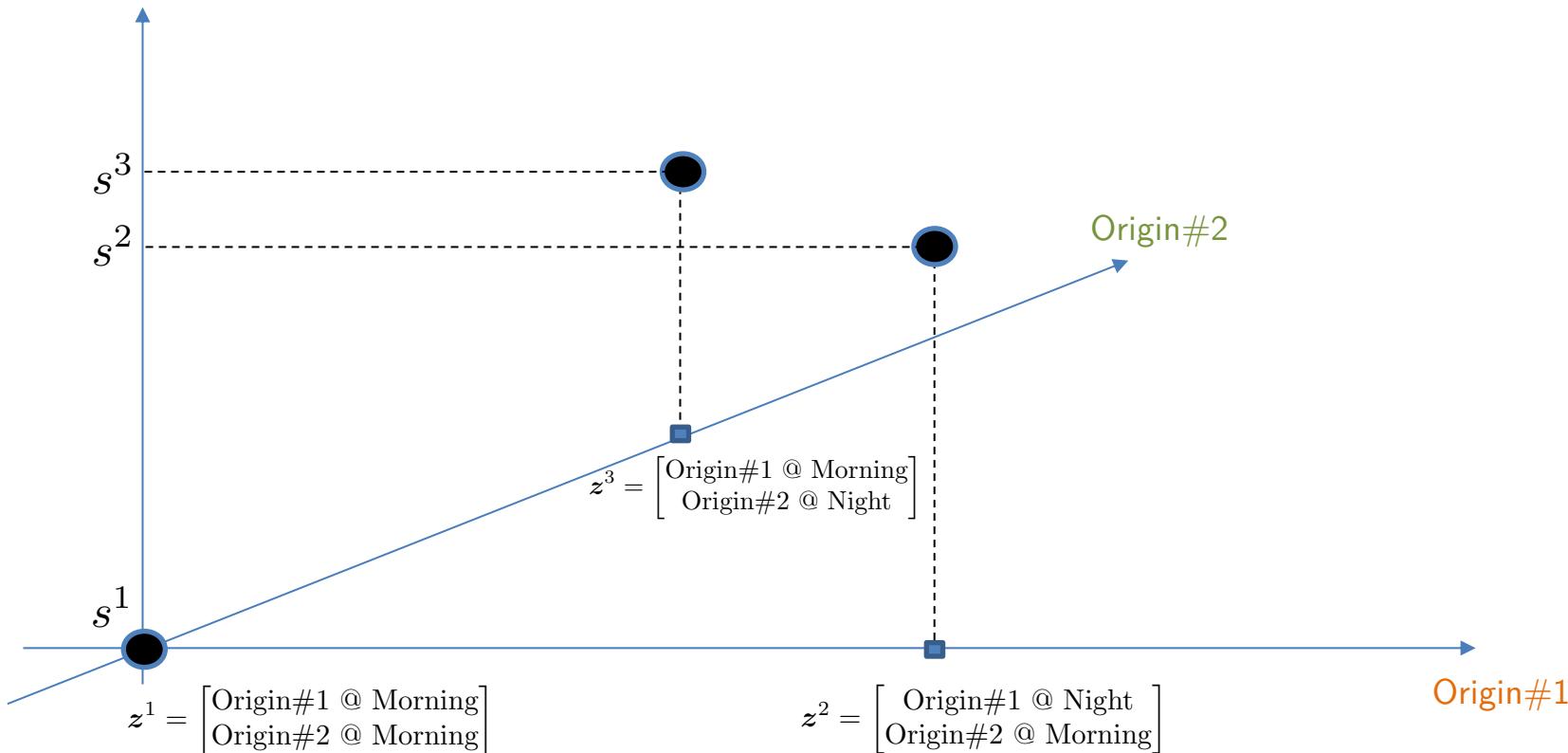
$\text{Speed}(z)$ = unique items that can be delivered in 1-day



$\text{Speed}(z)$ can be computed via a look-up table

The speed objective

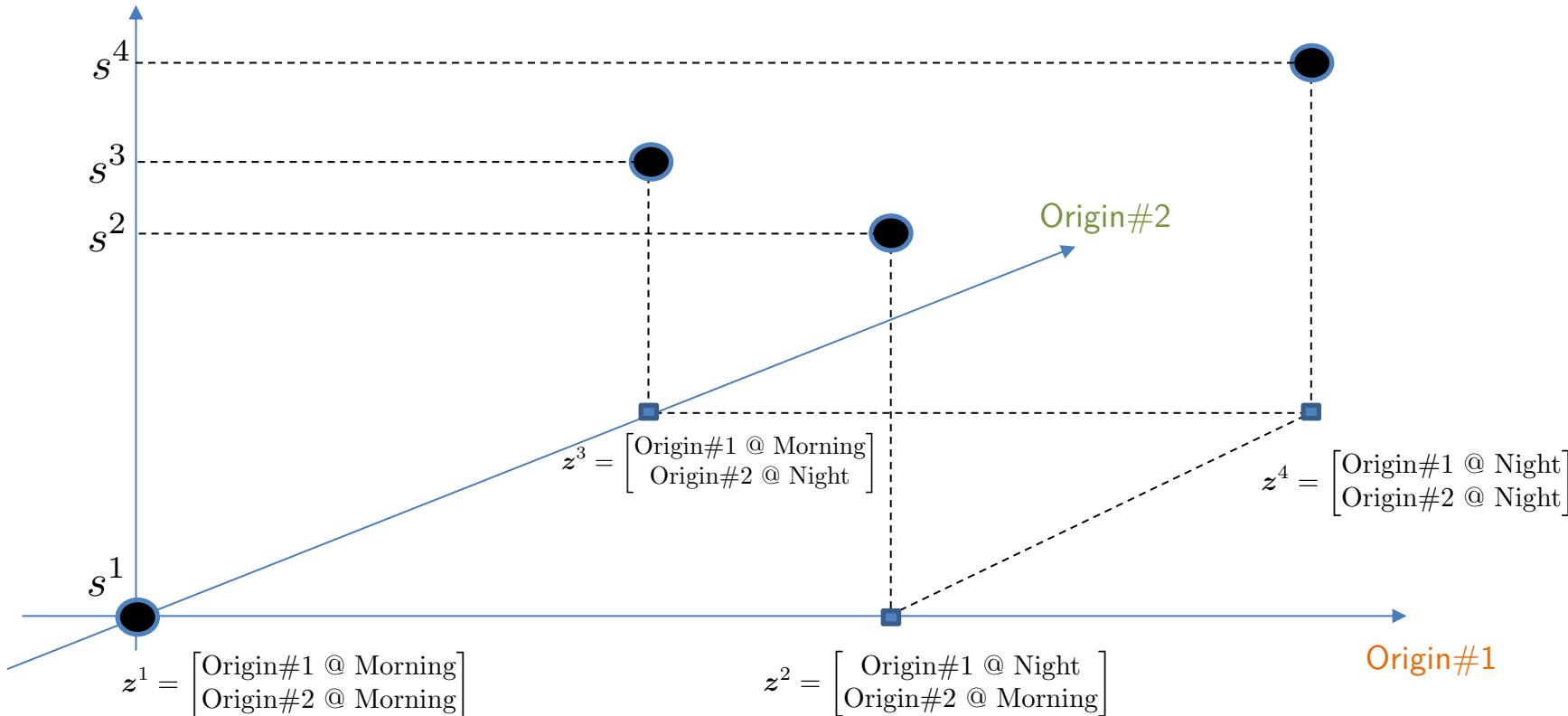
$\text{Speed}(z) = \text{unique items that can be delivered in 1-day}$



Speed(z) can be computed via a look-up table

The speed objective

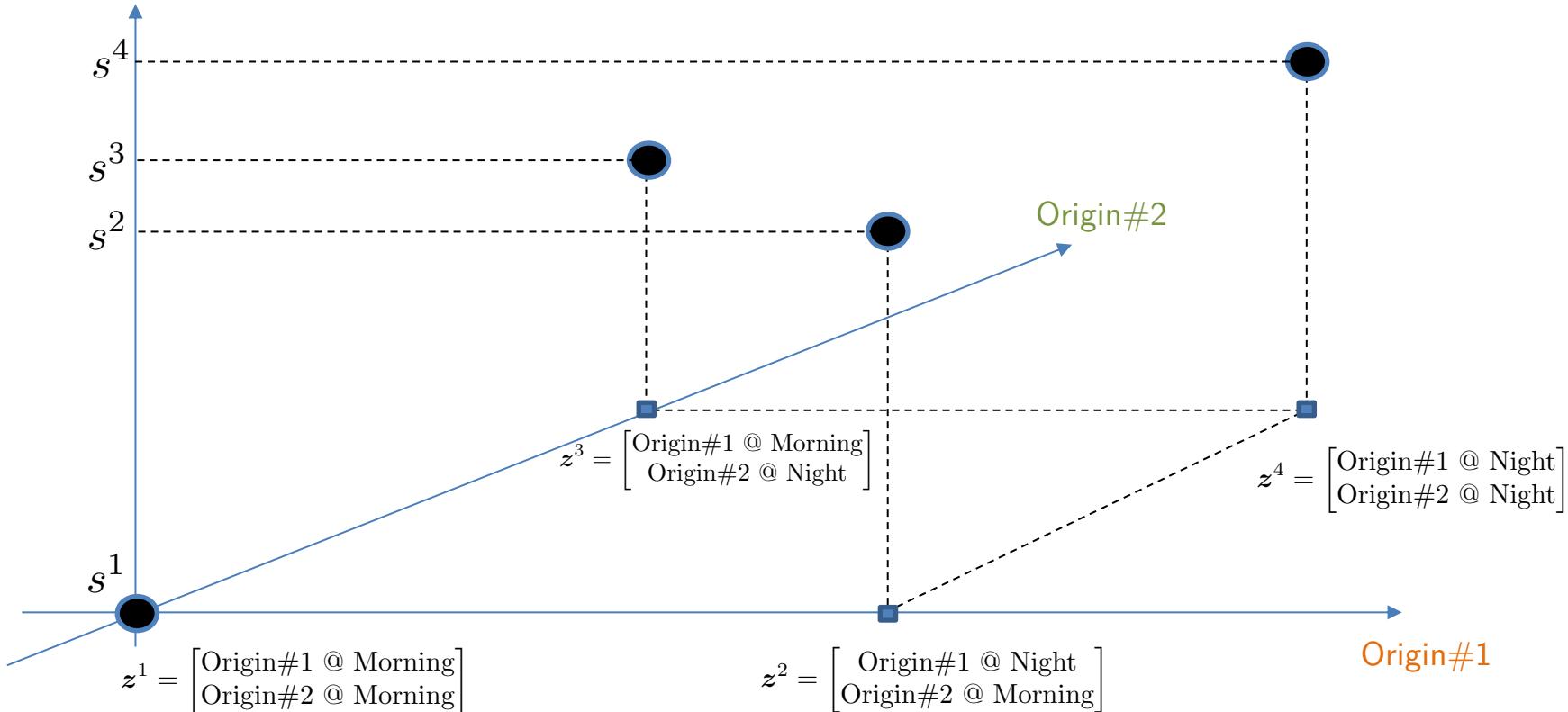
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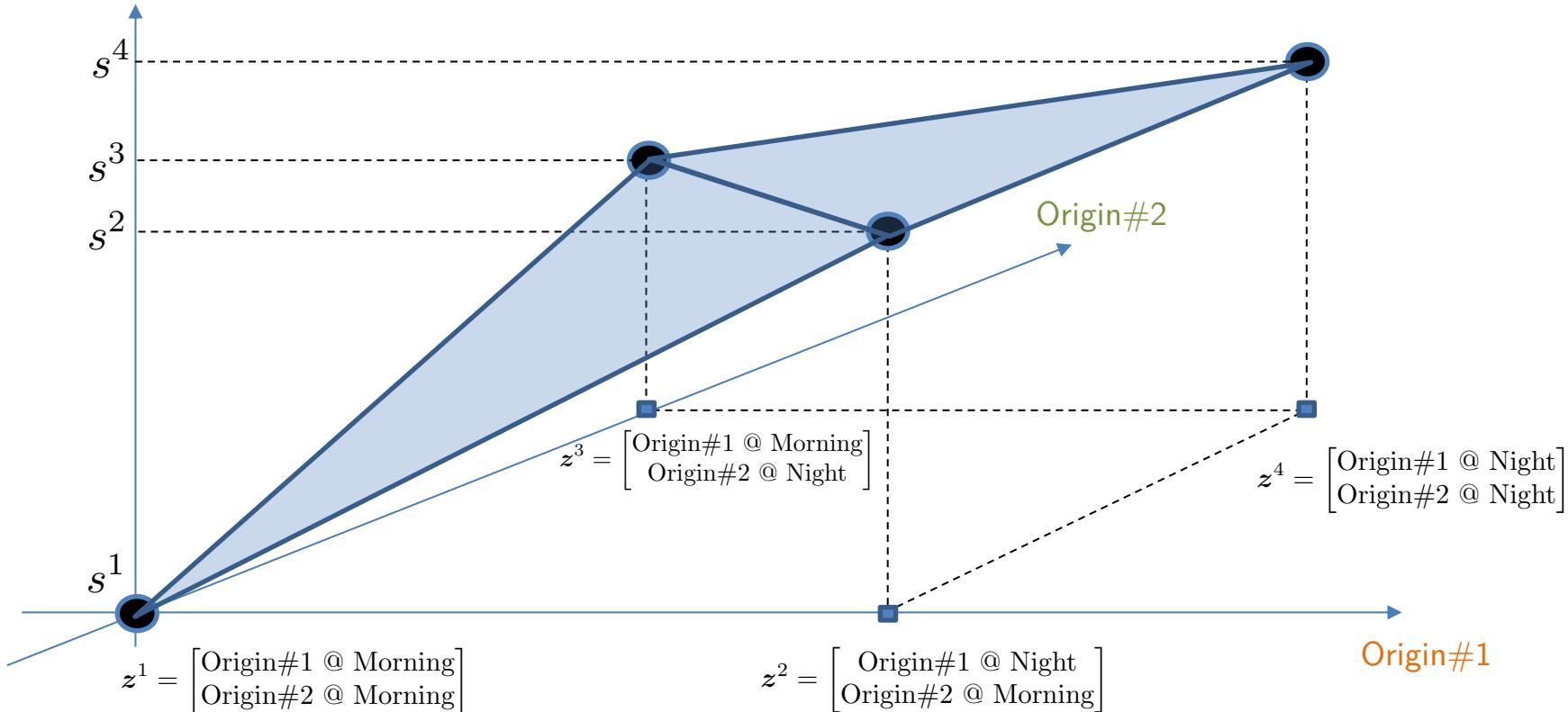
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Speed(z) can be computed via a look-up table

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$\text{Speed}(z) = \text{unique items that can be delivered in 1-day}$



Speed(z) can be computed via a look-up table

Approximating the speed objective

Approximating the speed objective

Step 1: Consider truck departure time combinations:

$$z^1 = \begin{bmatrix} \text{Origin\#1 @ Morning} \\ \text{Origin\#2 @ Morning} \end{bmatrix}, z^2 = \begin{bmatrix} \text{Origin\#1 @ Night} \\ \text{Origin\#2 @ Morning} \end{bmatrix}, z^3 = \begin{bmatrix} \text{Origin\#1 @ Morning} \\ \text{Origin\#2 @ Night} \end{bmatrix}, z^4 = \begin{bmatrix} \text{Origin\#1 @ Night} \\ \text{Origin\#2 @ Night} \end{bmatrix}$$

Approximating the speed objective

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Step 2: Compute speed for each combination:

$$s^i = \text{Speed}(z^i)$$

Approximating the speed objective

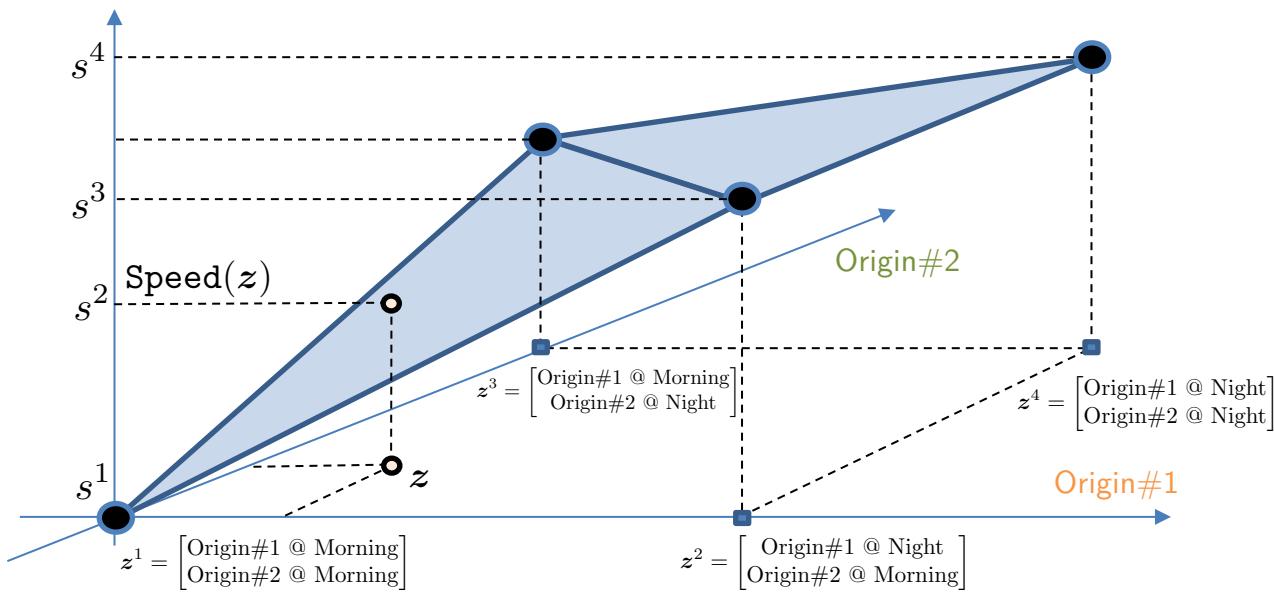
Step 1: Consider truck departure time combinations:

$$z^1 = \begin{bmatrix} \text{Origin\#1 @ Morning} \\ \text{Origin\#2 @ Morning} \end{bmatrix}, z^2 = \begin{bmatrix} \text{Origin\#1 @ Night} \\ \text{Origin\#2 @ Morning} \end{bmatrix}, z^3 = \begin{bmatrix} \text{Origin\#1 @ Morning} \\ \text{Origin\#2 @ Night} \end{bmatrix}, z^4 = \begin{bmatrix} \text{Origin\#1 @ Night} \\ \text{Origin\#2 @ Night} \end{bmatrix}$$

Step 2: Compute speed for each combination:

$$s^i = \text{Speed}(z^i)$$

Step 3: Interpolation via parametric optimization:



Approximating the speed objective

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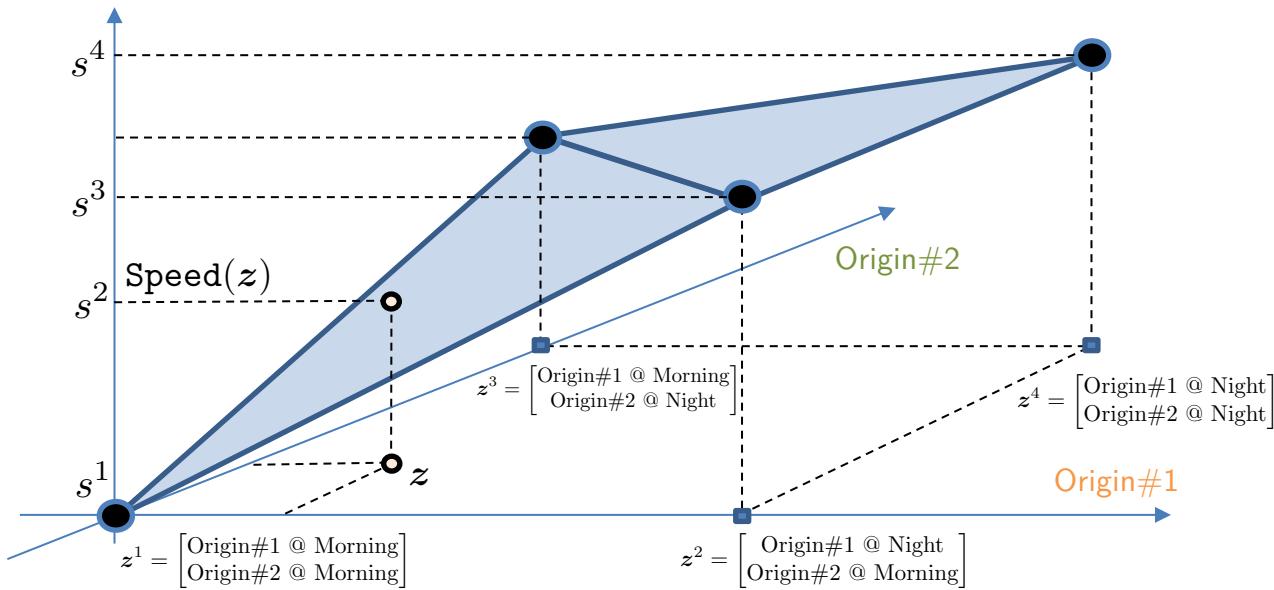
Step 3: Interpolation via parametric optimization:

$$\text{Speed}(z) = \max_{\alpha \geq 0} \sum_i \alpha^i s^i$$

subject to

$$\sum_i \alpha^i z^i = z$$

$$\sum_i \alpha^i_d = 1$$



Approximating the speed objective

Step 1: Consider truck departure time combinations:

$$z^1 = \begin{bmatrix} \text{Origin\#1 @ Morning} \\ \text{Origin\#2 @ Morning} \end{bmatrix}, z^2 = \begin{bmatrix} \text{Origin\#1 @ Night} \\ \text{Origin\#2 @ Morning} \end{bmatrix}, z^3 = \begin{bmatrix} \text{Origin\#1 @ Morning} \\ \text{Origin\#2 @ Night} \end{bmatrix}, z^4 = \begin{bmatrix} \text{Origin\#1 @ Night} \\ \text{Origin\#2 @ Night} \end{bmatrix}$$

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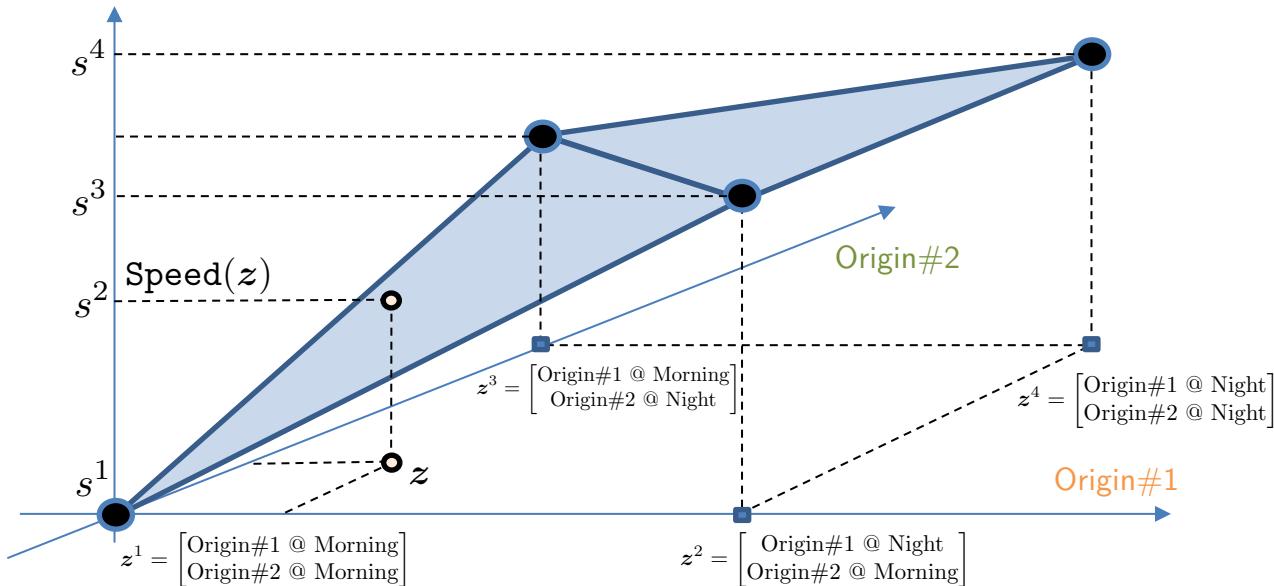
$$\text{Speed}(z) = \max_{\alpha \geq 0} \sum_i \alpha^i s^i$$

subject to

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Parameter defining the
optimal value of the LP

$$\sum_i \alpha_d^i = 1$$



Approximating the speed objective

Step 3: Interpolation via parametric optimization:

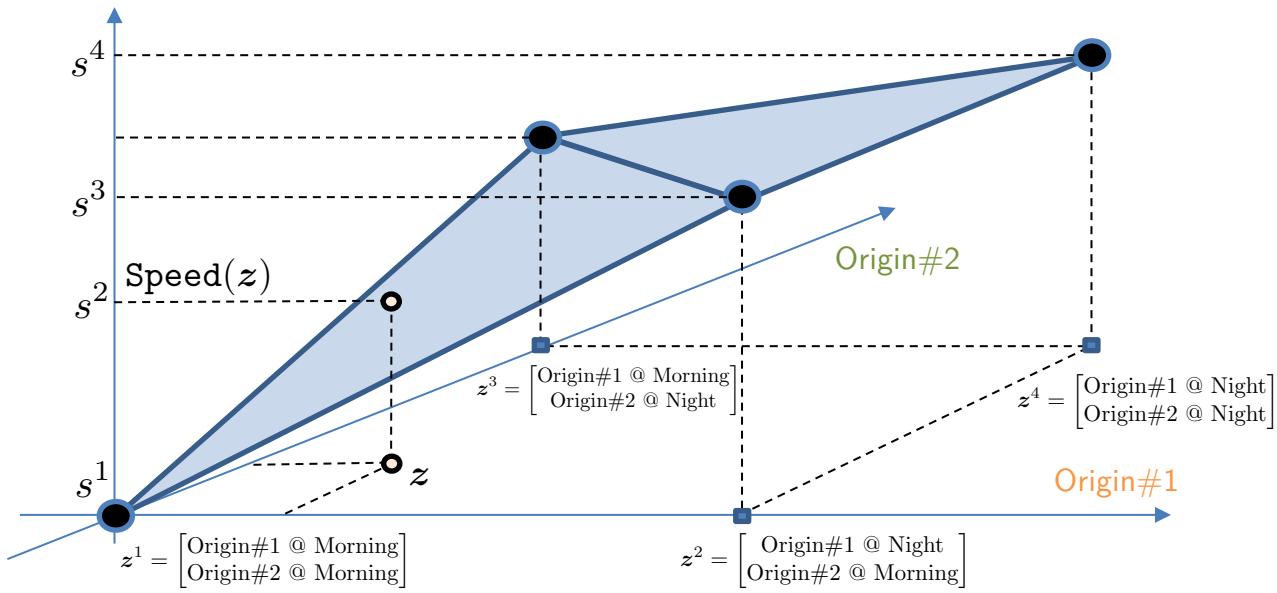
$$\text{Speed}(z) = \max_{\alpha \geq 0} \sum_i \alpha^i s^i$$

subject to $\sum_i \alpha^i z^i = z$

for defining the value of the LP

$$\sum_i \alpha_d^i = 1$$

Parameter defining the optimal value of the LP



Approximating the speed objective

$$\begin{aligned}
 \min_{p, y, z} \quad & \text{NetworkCost}(p, y) - \text{Speed}(z) \\
 \text{s.t.} \quad & (p, y) \in \text{FeasibleNetwork} \\
 & z \in \text{FeasibleSchedule}(p)
 \end{aligned}$$

Step 3: Interpolation via parametric optimization:

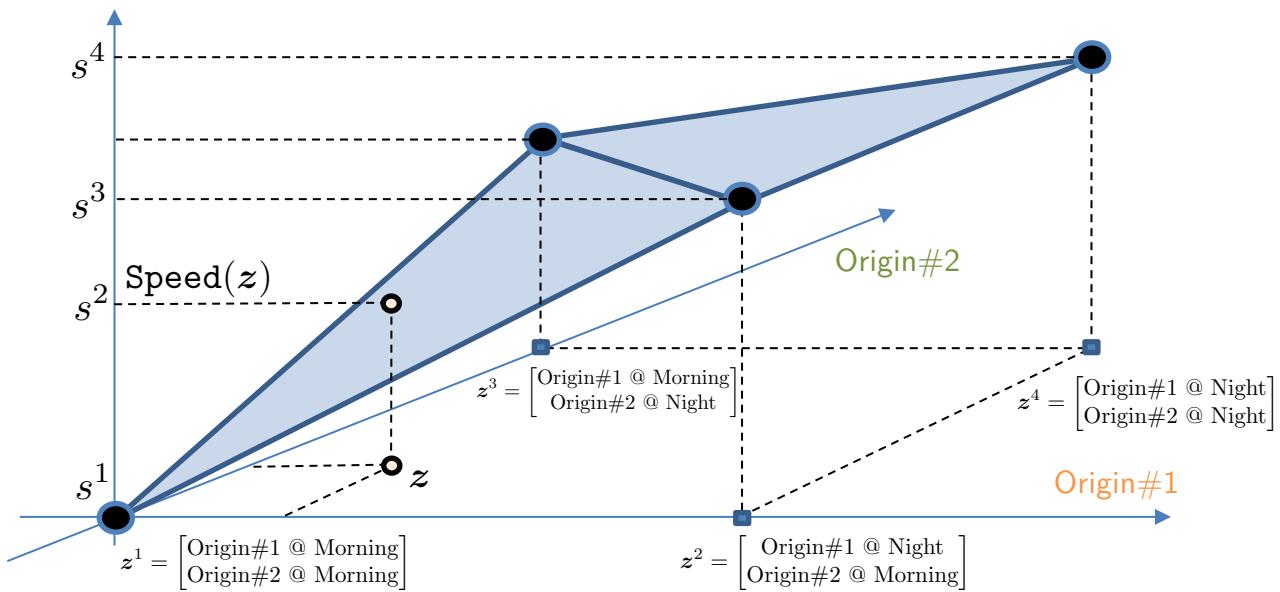
$$\text{Speed}(z) = \max_{\alpha \geq 0} \quad \sum_i \alpha^i s^i$$

subject to

$$\sum_i \alpha^i z^i = z$$

defining the value of the LP

$$\sum_i \alpha_d^i = 1$$



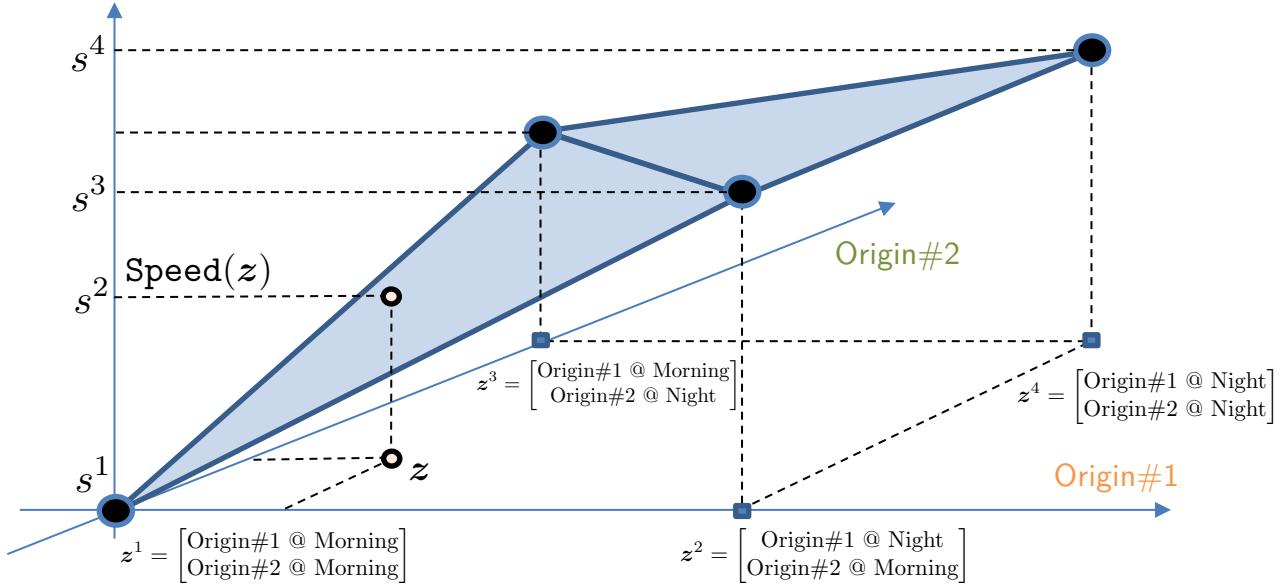
Approximating the speed objective

$$\begin{aligned}
 & \min_{\mathbf{p}, \mathbf{y}, \mathbf{z}, \boldsymbol{\alpha} > 0} \quad \text{NetworkCost}(\mathbf{p}, \mathbf{y}) - \sum_i \alpha^i s^i \\
 \text{s.t.} \quad & (\mathbf{p}, \mathbf{y}) \in \text{FeasibleNetwork}, \\
 & \mathbf{z} \in \text{FeasibleSchedule}(\mathbf{p}) \\
 & \sum_i \alpha^i z^i = z, \sum_i \alpha^i = 1
 \end{aligned}$$

Step 3: Interpolation via parametric optimization:

$$\begin{aligned}
 \text{Speed}(z) &= \max_{\boldsymbol{\alpha} \geq 0} \quad \sum_i \alpha^i s^i \\
 \text{subject to} \quad & \sum_i \alpha^i z^i = z \\
 & \sum_i \alpha^i = 1
 \end{aligned}$$

Parameter defining the optimal value of the LP



Outline

- ▶ Motivation
- ▶ Problem formulation
- ▶ Solution strategy
- ▶ Results

Results on a randomly generated datasets

Results on a randomly generated datasets

Results on 4 randomly generated datasets

- ▶ Location of nodes generated at random (cost of operating a truck proportional to distance)
- ▶ Items stored in each warehouse randomly generated
- ▶ Assuming a 0.1 conversion factor from speed and cost

Results on a randomly generated datasets

Results on 4 randomly generated datasets

- ▶ Location of nodes generated at random (cost of operating a truck proportional to distance)
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Speed parametric approximation compute by subsampling datapoint

Algorithm 1: Unique Items Approximation

```
1 Inputs:  $\kappa, \mathcal{D}, \mathcal{F}$ ;  
2 for  $d \in \mathcal{D}$  do  
3   Initialize  $\Lambda_d = \emptyset$ ;  
4   Sort by number of unique item the FCs that can offer 1-day delivery to DS  $d$ ;  
5   Compute the set  $\mathcal{Z}_d$  of all possible combinations of speed lane assignments for top  $\kappa$  FCs;  
6   For all  $z_d^i \in \mathcal{Z}_d$ , add the tuple  $(z_d^i, U_d(z_d^i))$  to the set  $\Lambda_d$ ;  
7   Compute the speed lane assignments from (12) for remaining  $(n_f - \kappa)$  FCs;  
8   For all  $\tilde{z}_d^i \in \tilde{\mathcal{Z}}_d$ , add the tuple  $(\tilde{z}_d^i, U_d(\tilde{z}_d^i))$  to the set  $\Lambda_d$ ;  
9 Return: Set of vectors and cost coefficients  $\Lambda_d$  for  $d \in \mathcal{D}$ .
```

Take all combination for top κ origins

Results on a randomly generated datasets

Baseline
method only
considering cost

n_F	n_D	Costs	App. Rev.	Rev.	Cost - (App. Rev.)	Cost - Rev.	κ	%Gap
10	10	689.1	-	342.8	689.1	346.3	-	0
10	10	698.5	383.7	383.7	314.8	314.8	1	0
10	10	698.5	383.7	383.7	314.8	314.8	5	0
10	10	698.5	383.7	383.7	314.8	314.8	10	0
10	20	1419.2	-	370.7	1419.2	677.7	-	1.8
10	20	1459.7	405.9	407	647.9	645.7	1	3.4
10	20	1434.1	397.8	400.7	638.5	632.7	5	2.8
10	20	1435.5	403.5	403.5	628.4	628.4	10	2.5
20	10	1392.2	-	770.4	1392.2	621.8	-	0.1
20	10	1422.9	807.3	815.7	615.6	607.2	1	0.1
20	10	1422.9	807.3	815.7	615.6	607.2	5	0.1
20	10	1413.6	806.5	811.2	607.1	602.4	10	0.1
50	10	3375.8	-	1845.2	3375.8	1530.6	-	1.8
50	10	3528.2	2010	2032.2	1518.2	1496.0	1	7.5
50	10	3499.0	2031.5	2039.1	1467.5	1459.9	5	3.8
50	10	3489.8	2025.3	2037.3	1464.4	1452.4	10	3.6
100	100	62204.2	-	3651.1	62204.2	25693.2	-	2.8
100	100	65911.4	4159.3	4175.7	24317.9	24154.2	1	11.2
100	100	65531.7	4156.8	4173.1	23963.2	23800.5	5	9.5
100	100	65258.6	4154.3	4172.1	23714.9	23537.2	10	8.4

8.36%
improvement
over baseline

Summary

Problem

- ▶ Speed and cost should be jointly optimised
- ▶ Speed objective is submodular and can be evaluated with a data query

Solution

- ▶ Leverage parametric optimization
- ▶ Subsampling strategy to reduce complexity

Results

- ▶ 8.36% speed and cost benefits compared to baseline
- ▶ No additional computational cost compared to baseline

