The pioneering spirit

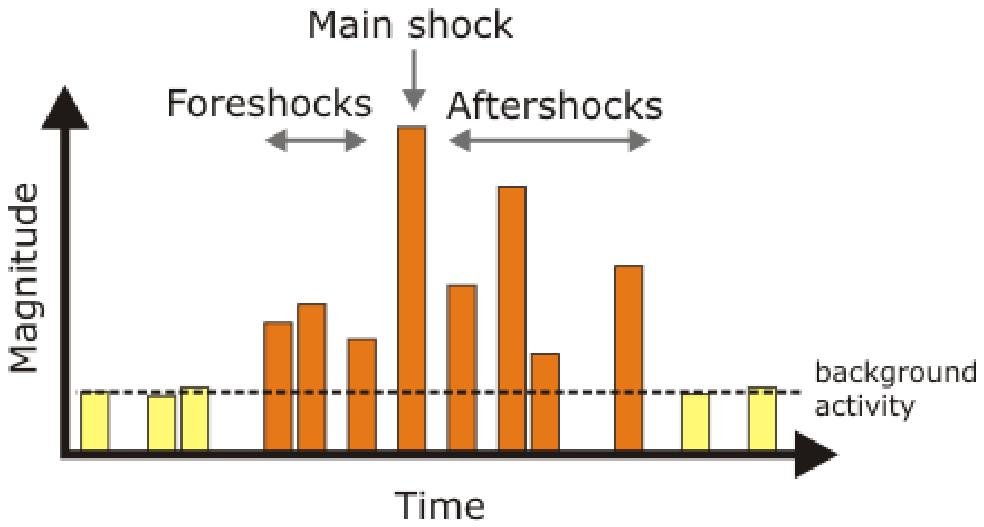
# Designing a robust supply chain of relief material for disaster preparedness with aftershocks: a branch-and-cut approach

*Minakshi Punam Mandal, **Laurent Alfandari**, Ivana Ljubic*
*ESSEC Business School*

## POC 13/12/2024, CNAM Paris

# Earthquakes and Aftershocks

- **Aftershocks are earthquakes that follow the largest shock of an earthquake sequence**
- They are typically smaller than the main shock, but the larger the main shock the larger and more numerous the aftershocks
- They can *continue over a period of weeks, months, or even years after the main shock*
- They can also trigger other emergencies like landslides, building collapses, tsunamis, etc.
- **This paper: focus on earthquakes, but can be generalized to any kind of disaster with aftershocks**



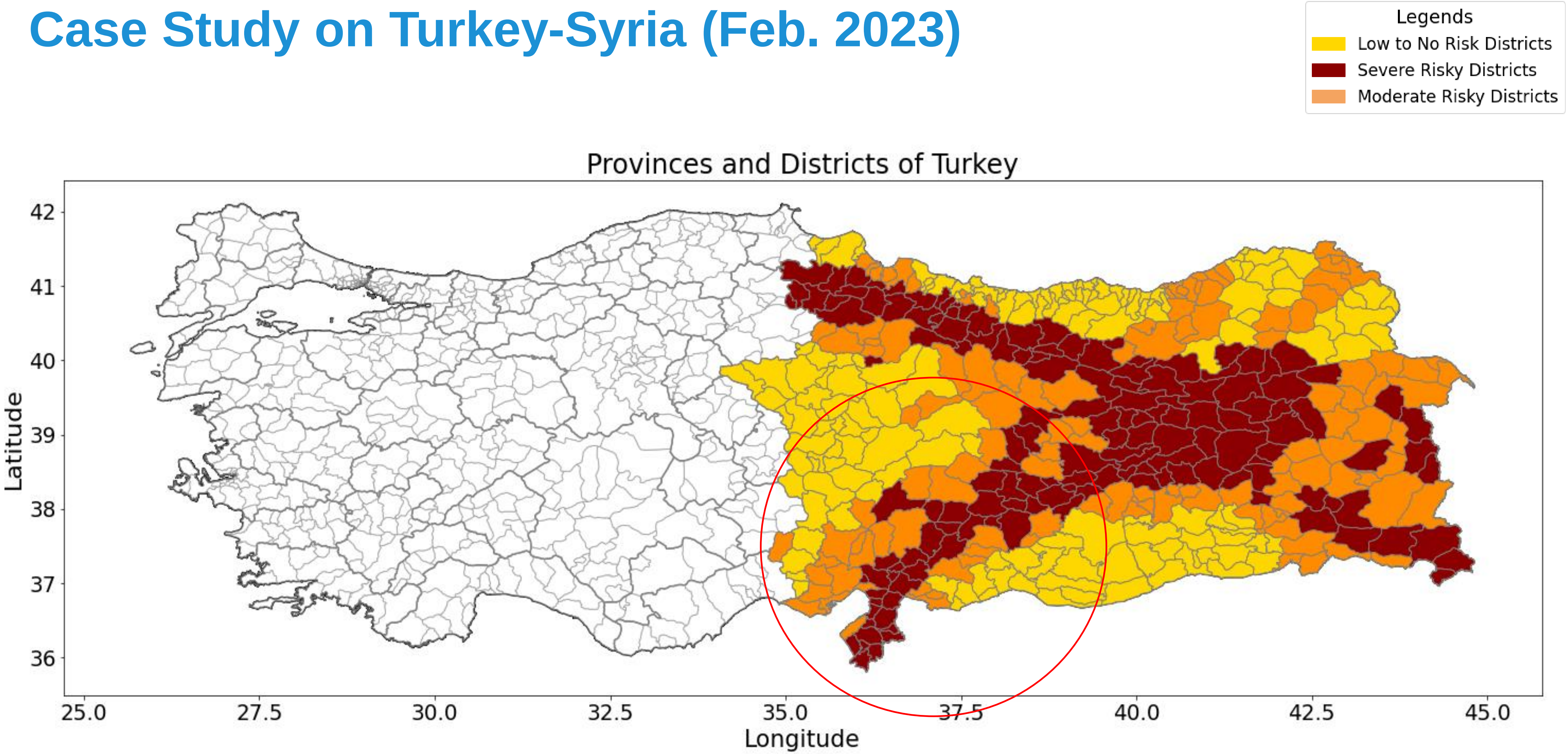

**Source:** https://all-geo.org/highlyallochthonous/2007/09/of-aftershocks-and-tsunamis/

ESSEC BUSINESS SCHOOL

# Motivation - Nepal Earthquake (2015)


- Caused landslides, avalanches, building collapses
- *3 major aftershocks* followed
- Deaths of approximately 9000 people, 16,800 injured, 2.8 million people displaced due to the *main earthquake and the aftershocks*
- The *last aftershock* alone resulted in over 200 deaths and over 2500 injured
- An *avalanche* caused by the earthquake killed 19 on Mt. Everest and stranded hundreds at the base camp

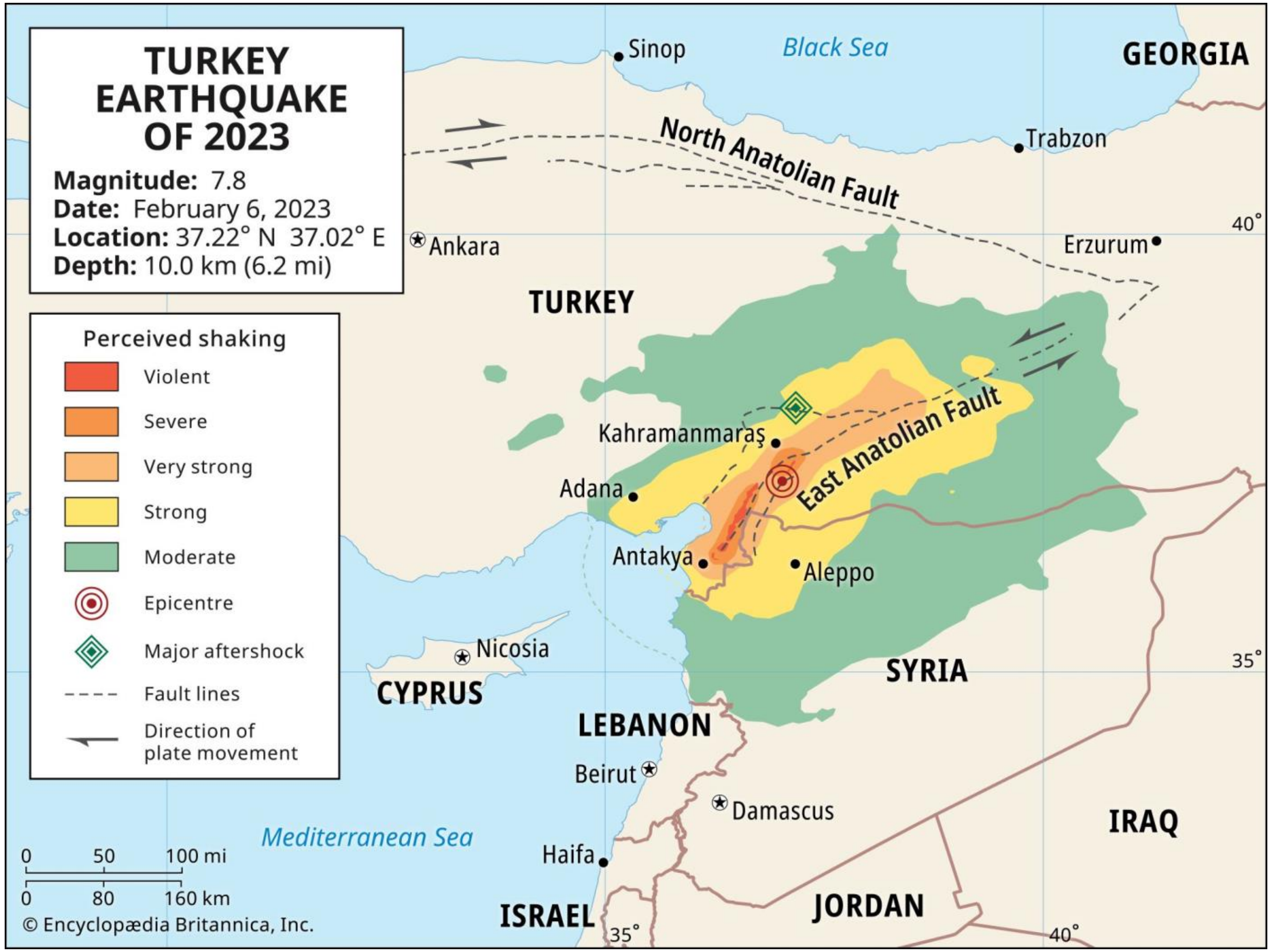
# Case Study on Turkey-Syria (Feb. 2023)



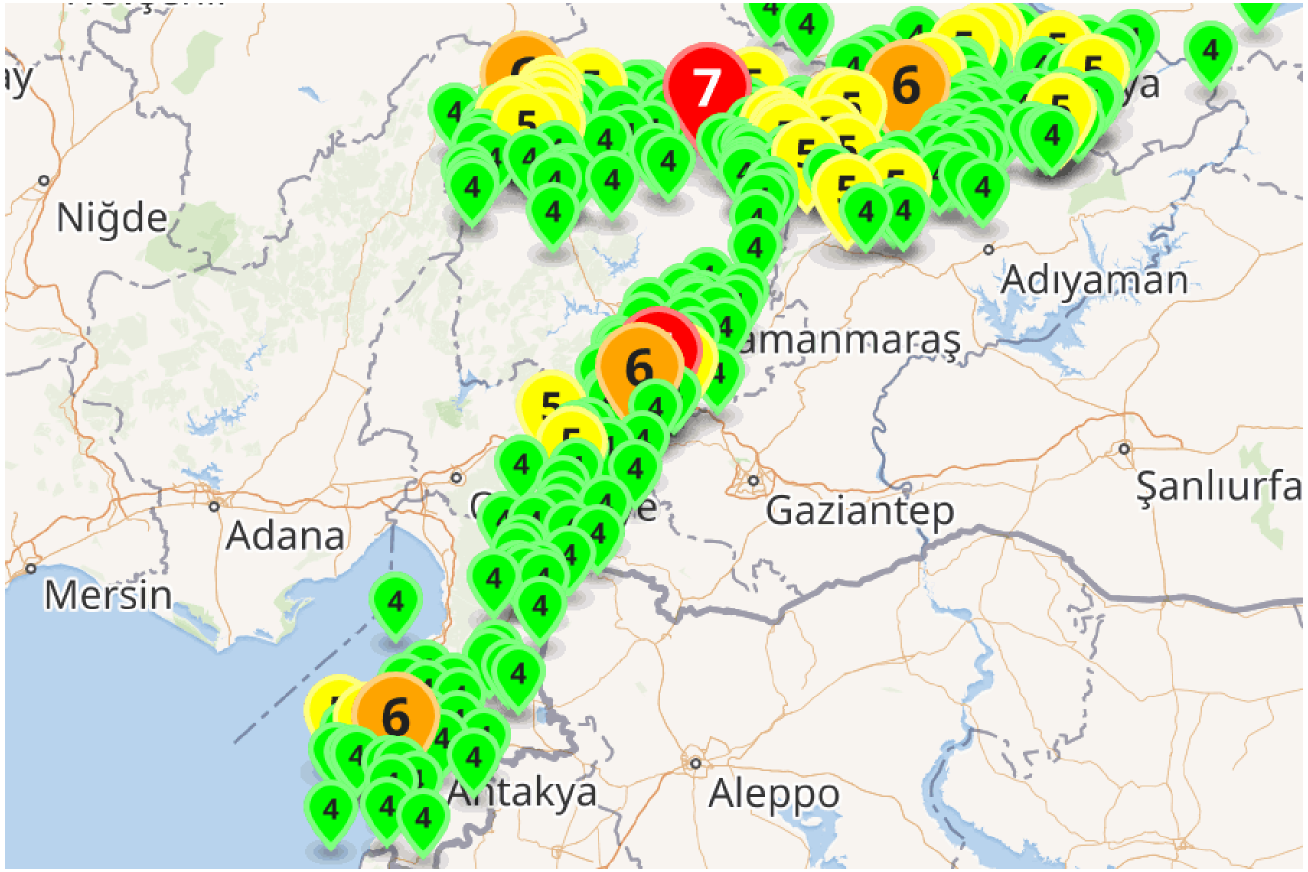
# Case Study on Turkey-Syria (Feb. 2023)

- Turkey and Syria were hit by a series of earthquakes

- First magnitude 7.8 earthquake on February 6



# Case Study on Turkey-Syria (Feb. 2023)




- + 570 aftershocks recorded within 24h of the $M_w$ 7.8 earthquake and over 30,000 recorded by May 2023.
- +25 aftershocks $M_w >= 4$ recorded within 6 h of the main earthquake
- Some regions were also hit by floods in the following months
- Syria already undergoing a humanitarian crisis

# Facility Location decisions- Problem setting

- ***Disaster Preparedness Phase- Location of Facilities***
- ***Strategic level of decision-making (Supply Chain network design)***
- ***Prepositioning of relief materials***, e.g., blankets, water, canned food, first-aid
- ***Earthquakes (1st-stage scenarios) with Aftershocks (2nd stage) in its 'vicinity'***
- To serve the demands of an area (Demand nodes) in a catastrophic event
- ***Robust Facility Location-*** Worst-case situation in the event of an earthquake with at most Δ aftershocks
- Uncapacitated Facilities (Warehouses)

**Assumptions:**

- No damage to Facilities due to earthquakes : located in "safe" places (or even in risky areas for earthquake-proof buildings)
- **2nd stage demand is caused by the closest aftershock**
- **Demand d** at a "demand" node = **f(population, distance to the earthquake or aftershock, magnitude) : d1,d2**

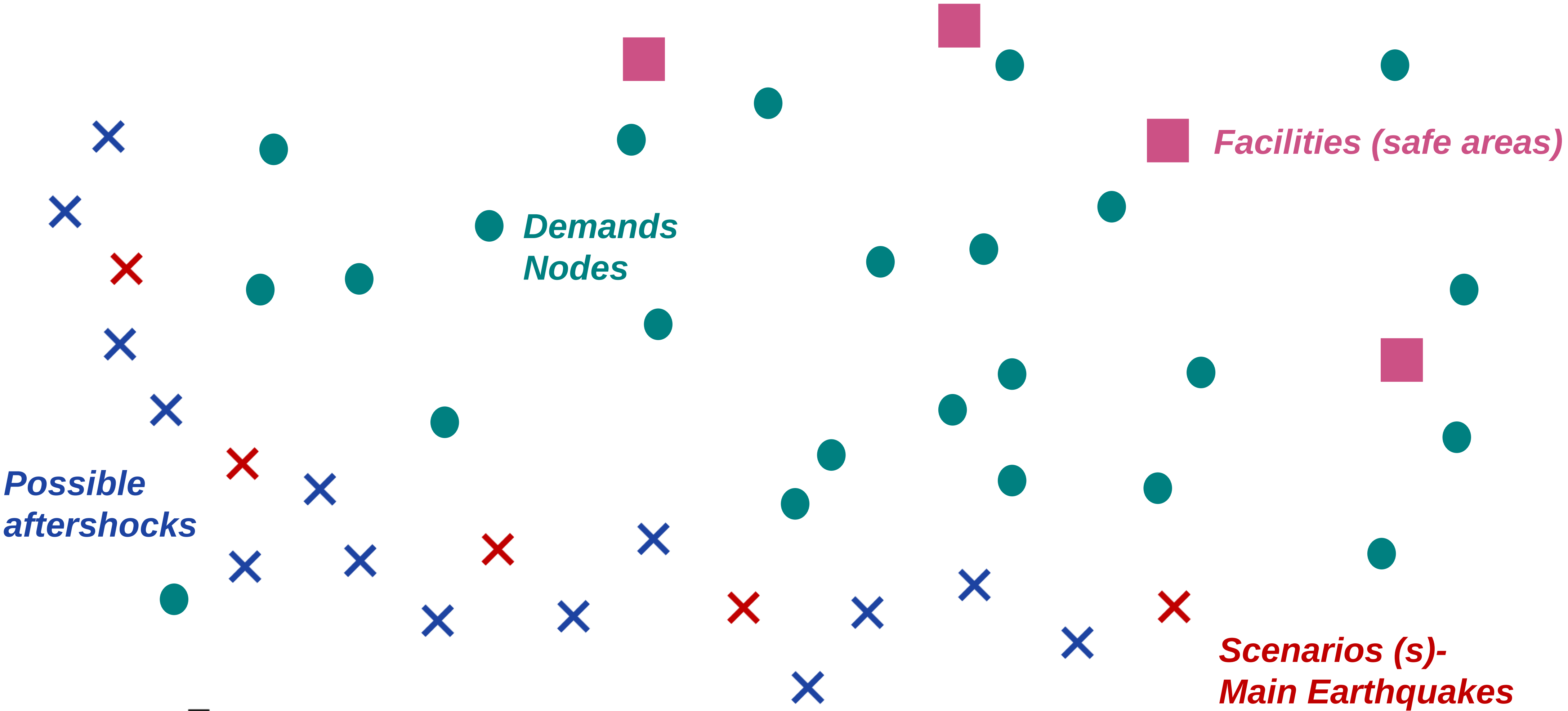
# Literature Review

- ***Facility location with Prepositioning-*** Balcik and Beamon (2008); Elci and Noyan (2018); Rezaei-Malek et al. (2016); Balcik et al. (2019)
- ***Facility location-allocation decisions-*** Paul and MacDonald (2016); Elci and Noyan (2018); Paul and Wang (2019)
- ***Facility location with disruptions-*** Salman and Yucel (2015); Paul and MacDonald (2016)
- ***Other types of facilities: shelter sites, relief distribution centers, casualty collection points, etc.-*** Lin et al. (2012); Lu and Sheu (2013); Alizadeh et al. (2019)
- ***Simultaneous disasters-*** Ozbay (2018); Ozbay et al. (2019)

**Facility location under uncertainty:** Mainly three kinds- ***uncertainty on the supply side, uncertainty on the demand side, uncertainties in the network*** (Donmez et al. 2021)

**We focus on uncertainty in the location of the disasters (specifically aftershocks), which results in demand uncertainty**

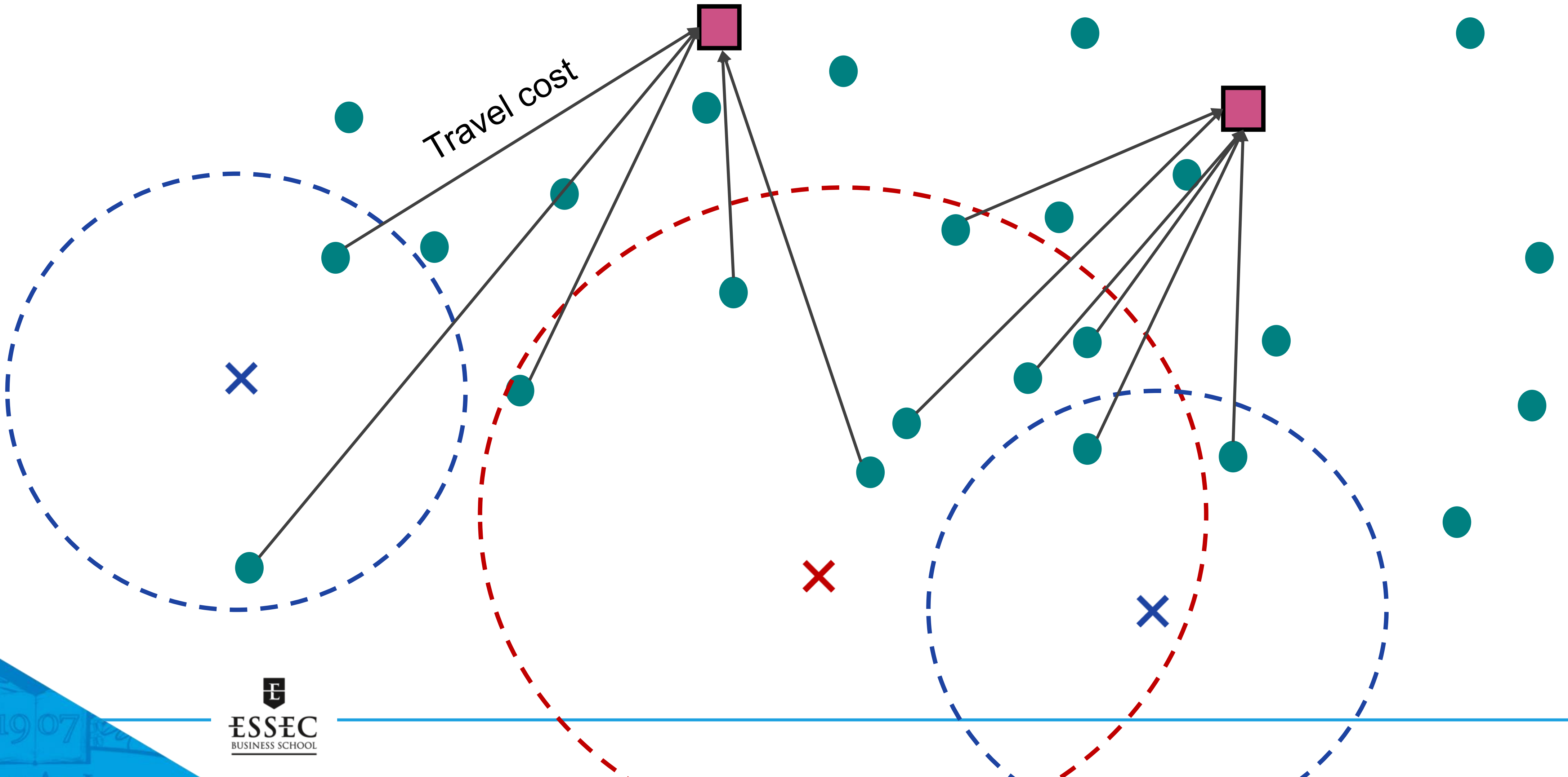
# Facility Location decisions- Problem setting



# Facility Location decisions- Problem setting

**(travel cost = travel time x demand; demand depends on closest shock location)**

**Whatever the demand, damaged cities are served by the closest open warehouse (uncapacitated)**



# Uncertainty set for aftershocks

$$\mathscr{K}_s^{\Delta} = \{K \subset \mathscr{K}_s : |K| \leq \Delta\}, \; s \in \mathscr{S}$$

$s$ = possible location of the main earthquake (1st stage scenario)
$S$ = set of scenarios of first earthquake $s$
$K$ = subset of aftershocks' locations in the vicinity of $s$
$K_s^{\Delta}$ = set of Δ aftershocks following scenario $s$

ESSEC BUSINESS SCHOOL

# Problem at a glance

***Stage 1 problem : minimize travel cost of demand nodes assigned to closest opened facility (demand based on scenario s)***

***Stage 2 problem : Same, but demand based on the location of the Δ aftershocks***

$$\min_{\substack{F\in\mathcal{F}\\ |F|\le N}} \left\{ \max_{s\in\mathcal{S}} \left\{ T_s^1(F) + \max_{K\in\mathcal{K}_s^\Delta} T_s^2(F,K) \right\} \right\}$$

***Select N facilities to open***

***Scenarios (Earthquakes)***

***Set of Δ aftershocks in Scenario $S$***

***Minimize the allocation cost in the worst-case demand scenario***

**WE PROPOSE FOUR MODELING/SOLVING APPROACHES**

# 1. Model $P_{xy\text{-full}}$: Full enumeration of all two-stage « aggregated » scenarios

worst-case allocation cost

The aggregated set of scenarios of type (s,K)

$$
\begin{aligned}
\mathbf{P_{xy}}:\quad & \min\ \theta \\
\text{subject to}\quad & \theta \geq \sum_{i\in\mathscr{D}}\sum_{j\in\mathscr{F}} t_{ij}(d^1_{\omega i}+d^2_{\omega i})x_{ij} \qquad \omega\in\Omega \\
& \sum_{j\in\mathscr{F}} x_{ij} = 1 \qquad i\in\mathscr{D} \\
& y_j \geq x_{ij} \qquad i\in\mathscr{D},\ j\in\mathscr{F} \\
& 1 \leq \sum_{j\in\mathscr{F}} y_j \leq N \\
& \theta \geq 0 \\
& x_{ij}, y_j \in \{0,1\} \qquad i\in\mathscr{D},\ j\in\mathscr{F}
\end{aligned}
$$

Minimize the cost of allocating the demand nodes to the facilities

**Tractable only for very small instances!**
**(requires to enumerate all subsets of Δ aftershocks in Ω)**

$x_{ij}$ = 1 iff city $i$ is supplied by (closest) facility $j$ (opened iff $y_j$ = 1)

ESSEC BUSINESS SCHOOL

# 2. Model Pxy-sep : Branch-and-Cut algorithm: Separation of aggregated scenarios

$$\theta \geq \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij}(d^1_{\omega i} + d^2_{\omega i})x_{ij}$$

$$\tau^1_s(x^*) = \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij} d^1_{si} x^*_{ij}$$

*First-stage allocation cost*

$$\tau^2_s(x^*) = \max \sum_{i \in \mathscr{D}} \left( \sum_{j \in \mathscr{F}} t_{ij} x^*_{ij} \right) \max_{k \in \mathscr{K}_s} \{ d^2_{ik} u_k \}$$

$$\sum_{k \in \mathscr{K}_s} u_k \leq \Delta$$

$$u_k \in \{0,1\} \qquad k \in \mathscr{K}_s.$$

*Second-stage worst allocation cost*

Demand of i depending on the aftershocks' locations

→ **$u_k = 1$ if there is an aftershock at location $k$**

→ Solvable as a MILP

# 2. Model Pxy-sep : Branch-and-Cut algorithm:

## Separation of aggregated scenarios : MILP reformulation of 2nd-stage

$$\theta \geq \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij}(d^1_{\omega i} + d^2_{\omega i})x_{ij}$$

With $\boldsymbol{C_{ik}} = (\sum_j \boldsymbol{t_{ij}}\, \boldsymbol{x^*_{ij}})\, \boldsymbol{d^2_{sik}}$

$$\tau^1_s(x^*) = \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij} d^1_{si} x^*_{ij}$$

***First-stage allocation cost***

$$\tau^2_s(x^*) = \max \sum_{i \in \mathscr{D}} \sum_{k \in \mathscr{K}_s} C_{ik} z_{ik}$$

$$\sum_{k \in \mathscr{K}_s} z_{ik} = 1 \qquad i \in \mathscr{D}$$

$$z_{ik} \leq u_k \qquad i \in \mathscr{D}, k \in \mathscr{K}_s$$

$$\sum_{k \in \mathscr{K}_s} u_k \leq \Delta$$

$$u_k \in \{0,1\} \qquad k \in \mathscr{K}_s$$

$$z_{ik} \geq 0 \qquad i \in \mathscr{D}, k \in \mathscr{K}_s$$

***Second-stage worst allocation cost = max p-median (MILP)***

→ $u_k = 1$ **if there is an aftershock at** $k$

→ $z_{ik} = 1$ **if** $k$ **is the closest aftershock from** $i$

ESSEC BUSINESS SCHOOL

# 2. Model $P_{xy\text{-}sep}$ :Branch-and-Cut Algorithm

## Cut Generation Scheme

We verify that for **each** 1st-stage (main earthquake) scenario s :

$$\theta^* \geq \tau_s^1(x^*) + \tau_s^2(x^*)$$

**If not satisfied for some** $\boldsymbol{s}$, we add the constraint (cut) corresponding to the violated aggregated scenario $\bar{\omega} = (s, K)$ (such $K$, or $u^*$ vector, is easy to find, see next slide)

$$\theta \geq \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij}(d^1_{i\bar{\omega}} + d^2_{i\bar{\omega}})x_{ij}$$

ESSEC BUSINESS SCHOOL

# 3. Model Pxy-ext : Extended Formulation (upper bound heuristic)

## Based on Dualization of 2nd-stage subproblem $\tau_s^2(x^*)$ LP-relaxation

$$\tau_s^2(x^*) = \max \sum_{i\in\mathscr{D}}\sum_{k\in\mathscr{K}_s} C_{ik} z_{ik}$$

$$\sum_{k\in\mathscr{K}_s} z_{ik} = 1 \qquad i\in\mathscr{D}$$

$$z_{ik} \le u_k \qquad i\in\mathscr{D}, k\in\mathscr{K}_s$$

$$\sum_{k\in\mathscr{K}_s} u_k \le \Delta$$

$$u_k \in \{0,1\} \qquad k\in\mathscr{K}_s$$

$$z_{ik} \ge 0 \qquad i\in\mathscr{D}, k\in\mathscr{K}_s$$

With $C_{ik} = \left(\sum_j t_{ij}\, x_{ij}^*\right) d_{sik}^2$

$z_{ik} = 1$ iff $k$ is the closest aftershock from $i$

**Dualize with relaxed $0 \le u_k \le 1$**

**(note: we obtain an upper bound on θ* in theory… but the LP-relaxation happened to be 0-1 on ALL instances (!!!) )**

$$\tau_s^2(x^*) = \min \sum_{i\in\mathscr{D}} p_{si} + \Delta\phi_s + \sum_{k\in\mathscr{K}_s} r_{sk}$$

$$p_{si} + q_{sik} \ge \sum_{j\in\mathscr{F}} t_{ij} d_{ik}^2 x_{ij}^* \qquad i\in\mathscr{D}, k\in\mathscr{K}_s$$

$$-\sum_{i\in\mathscr{D}} q_{sik} + \phi_s + r_{sk} \ge 0 \qquad k\in\mathscr{K}_s$$

$$q_{sik}, r_{sk}, \phi_s \ge 0, p_{si}\in\mathbb{R} \qquad i\in\mathscr{D}, k\in\mathscr{K}_s, s\in\mathscr{S}$$

# 3. Model Pxy-ext : Extended Formulation

# Final (compact) model after dualization

$$
\begin{aligned}
\mathbf{F}_{\mathbf{xy}}^{\mathbf{ext}}: \quad & \min \ \theta \\
\text{subject to} \quad & \theta \geq \sum_{i\in\mathscr{D}} \sum_{j\in\mathscr{F}} t_{ij} d^1_{si} x_{ij} + \sum_{i\in\mathscr{D}} p_{si} + \Delta\phi_s + \sum_{k\in\mathscr{K}_s} r_{sk} && s \in \mathscr{S} \\
& p_{si} + q_{sik} \geq \sum_{j\in\mathscr{F}} t_{ij} d^2_{ik} x_{ij} && i \in \mathscr{D}, k \in \mathscr{K}_s \\
& -\sum_{i\in\mathscr{D}} q_{sik} + \phi_s + r_{sk} \geq 0 && k \in \mathscr{K}_s \\
& \sum_{j\in\mathscr{F}} x_{ij} \geq 1 && i \in \mathscr{D} \\
& y_j \geq x_{ij} && i \in \mathscr{D},\ j \in \mathscr{F} \\
& 1 \leq \sum_{j\in\mathscr{F}} y_j \leq N \\
& \theta \geq 0 \\
& x_{ij}, y_j \in \{0,1\} && i \in \mathscr{D},\ j \in \mathscr{F} \\
& q_{sik}, r_{sk}, \phi_s \geq 0, p_{si} \in \mathbb{R} && i \in \mathscr{D}, j \in \mathscr{F}, k \in \mathscr{K}_s, s \in \mathscr{S}
\end{aligned}
$$

***Adding the dualized second-stage subproblem***

- **Directly solvable by a MILP solver**
- Happened to be systematically optimal (good property of **p-median LP-relaxation**)

ESSEC BUSINESS SCHOOL

# 4. Formulation $\mathrm{F_y}$ (in the space of only y variables)

## Recall (general) problem :

$$\min_{\substack{F \in \mathscr{F} \\ |F| \leq N}} \left\{ \max_{s \in \mathscr{S}} \left\{ \boxed{T_s^1(F)} + \max_{K \in \mathscr{K}_s^{\Delta}} \boxed{T_s^2(F,K)} \right\} \right\}$$

***Stage 1 subproblem***

***Stage 2 subproblem***

ESSEC BUSINESS SCHOOL

# 4. Formulation $\mathbf{F_y}$ (in the space of only y variables): First-stage subproblem $T_s^1$

$$T_s^1(y^*) = \min_x \sum_{i\in\mathscr{D}} d_{si}^1 \sum_{j\in\mathscr{F}} t_{ij}\, x_{ij}$$

$$\sum_{j\in\mathscr{F}} x_{ij} = 1 \qquad i \in \mathscr{D}$$

$$0 \le x_{ij} \le y_j^* \qquad i \in \mathscr{D},\ j \in \mathscr{F}$$

**Primal and Dual Solutions**

$$x_{ij} = \begin{cases} y_j^*, & j < p_i \\ 1 - \sum_{j=1}^{p_i - 1} y_j^*, & j = p_i\,, \\ 0, & j > p_i \end{cases} \qquad j \in \mathscr{F}$$

$$\lambda_i = t_{ip_i} d_{si}^1$$

$$\mu_{ij} = \begin{cases} (t_{ip_i} - t_{ij}) d_{si}^1, & j < p_i \\ 0, & j \ge p_i \end{cases}, \qquad i \in \mathscr{D},\ j \in \mathscr{F}$$

Substitute in Primal
the assignment variables $x$
by a closed-loop expression in $y^*$
*(possible for Uncapacitated problems)*
*$p_i$ = critical facility for i (closest opened)*

# 4. Formulation $\mathbf{F_y}$ : Second-stage subproblem $T_s^2$

$$
\begin{aligned}
T_s^2(y^*, u_s^*) = \min_{z_s} & \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij} \, z_{sij} \\
& \sum_{j \in \mathscr{F}} z_{sij} \geq u_{sk}^* \, d_{ik}^2 \qquad i \in \mathscr{D}, \, k \in \mathscr{K}_s \\
& z_{sij} \leq \widehat{D}_i y_j^* \qquad i \in \mathscr{D}, j \in \mathscr{F} \\
& z_{sij} \geq 0 \qquad i \in \mathscr{D}, \, j \in \mathscr{F}.
\end{aligned}
$$

**Dualize the LP**

$$
\begin{aligned}
\max_{u_s \in \mathscr{K}_s^{\Delta}} T_s^2(y^*, u_s) = \max_{\alpha_s, \beta_s, u_s} & \sum_{i \in \mathscr{D}} \sum_{k \in \mathscr{K}_s} d_{ik}^2 \, \alpha_{sik} - \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} \widehat{D}_i y_j^* \, \beta_{sij} \\
\text{subject to:} & \sum_{k \in \mathscr{K}_s} \alpha_{sik} - \beta_{sij} \leq t_{ij}, \quad i \in \mathscr{D}, \, j \in \mathscr{F} \\
& \sum_{k \in \mathscr{K}_s} u_{sk} \leq \Delta \\
& \alpha_{sik} \leq M u_{sk}, \quad i \in \mathscr{D}, \, k \in \mathscr{K}_s \\
& \alpha_{sik}, \, \beta_{sij}, \geq 0, \, u_{sk} \in \{0, 1\}, \quad i \in \mathscr{D}, \, j \in \mathscr{F}, \, k \in \mathscr{K}_s
\end{aligned}
$$

# 4. Formulation $\mathbf{F_y}$: Branch-and-Cut Algorithm- Cut Generation Scheme

$$\mathbf{F_y}: \quad \min \quad \theta$$

$$\theta \geq \sum_{i\in\mathscr{D}} d^1_{si}\left[t_{ip_i} - \sum_{j\in\mathscr{F}}(t_{ip_i} - t_{ij})^+ y_j\right] + \sum_{i\in\mathscr{D}}\sum_{k\in\mathscr{K}_s} d^2_{ik}\,\alpha^*_{sik} - \sum_{i\in\mathscr{D}}\sum_{j\in\mathscr{F}} \widehat{D}_i y_j \beta^*_{sij},$$

$$(p_1,\ldots,p_{|\mathscr{D}|}) \in \mathscr{F}^{|\mathscr{D}|}, (\alpha^*,\beta^*,u^*) \in \mathscr{L}^2_s, s \in \mathscr{S}$$

$$1 \leq \sum_{j\in\mathscr{F}} y_j \leq N, \qquad j \in \mathscr{F}$$

$$\theta \geq 0, y_j \in \{0,1\} \qquad j \in \mathscr{F}$$

ESSEC BUSINESS SCHOOL

# 4. Solution Approach $\mathrm{P_y}$ Branch-and-Cut Algorithm- Cut Generation Scheme

If for a given solution $(\bar{\theta}, \bar{y})$ of the master we have for some scenario $\tilde{s}$:

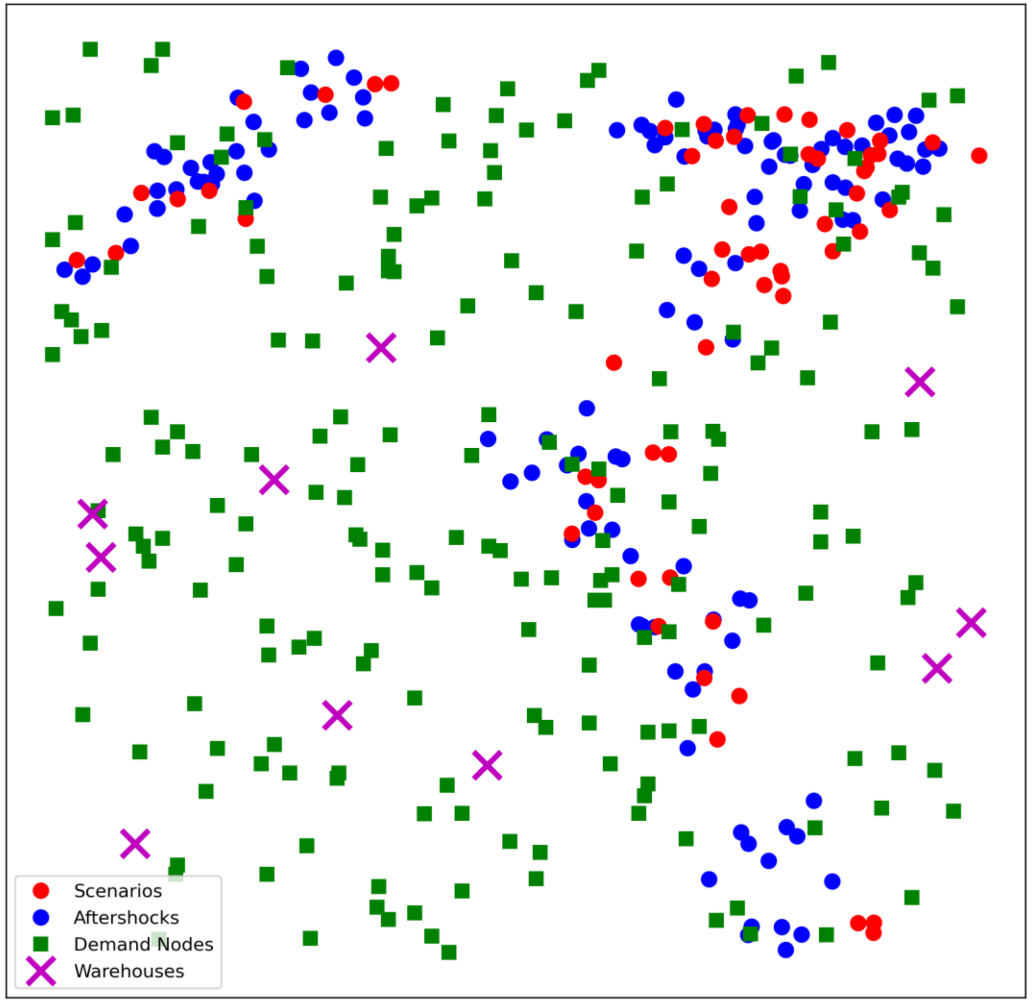
$$\bar{\theta} < \sum_{i\in\mathscr{D}} d^1_{i\tilde{s}} \left[ t_{i\bar{p}_i} - \sum_{j\in\mathscr{F}} (t_{i\bar{p}_i} - t_{ij})^+ \bar{y}_j \right] + \sum_{i\in\mathscr{D}} \sum_{k\in\mathscr{K}_{\tilde{s}}} d^2_{ik}\, \alpha^*_{i\tilde{s}k} - \sum_{i\in\mathscr{D}} \sum_{j\in\mathscr{F}} \widehat{D}_i \bar{y}_j \beta^*_{ij\tilde{s}}$$

Then we add the corresponding cut for this $s = \tilde{s}$:

(note : the cut uses variables $y$ but not $x$) :

$$\theta \geq \sum_{i\in\mathscr{D}} d^1_{si} \left[ t_{ip_i} - \sum_{j\in\mathscr{F}} (t_{ip_i} - t_{ij})^+ y_j \right] + \sum_{i\in\mathscr{D}} \sum_{k\in\mathscr{K}_s} d^2_{ik}\, \alpha^*_{sik} - \sum_{i\in\mathscr{D}} \sum_{j\in\mathscr{F}} \widehat{D}_i y_j \beta^*_{sij},$$

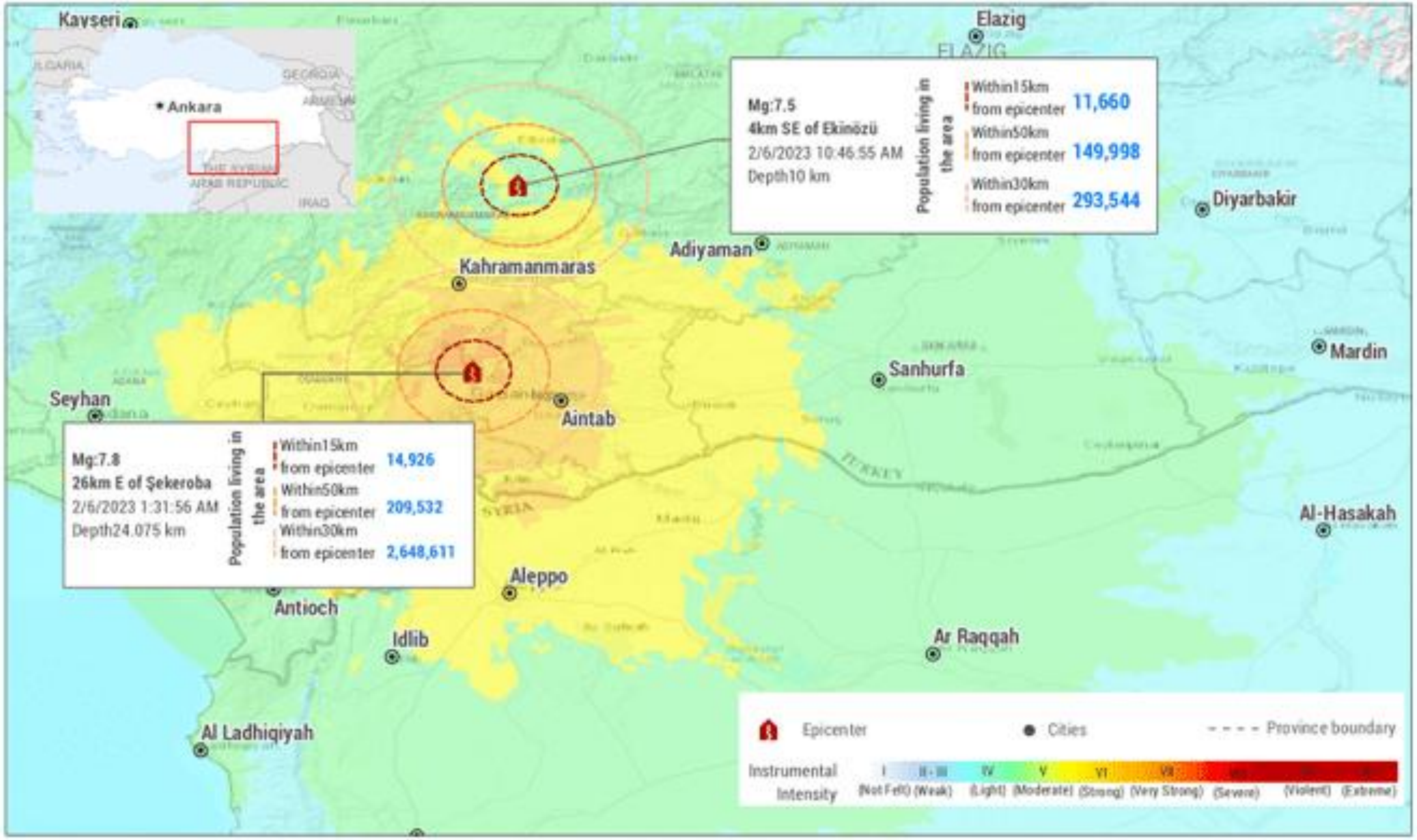
# Numerical Experiments: Generation of Instances




- # demand nodes : 100 (Small), 200 (Medium), 400 (Large)
- # main earthquake scenarios s : 10, 20, 30,.., 100
- # possible aftershocks : 20, 40, …, 200
- # possible facilities : 10 (N = 3, 5, 8)
- Δ = 3, 5, 7, 10
- Total of 360 instances

ESSEC BUSINESS SCHOOL

# Turkey earthquake in Gaziantep on Feb 2023




**Source:** OCHA, https://reliefweb.int/map/turkiye/turkiye-earthquakes-southern-turkiye-06-february-2023-06-february

# Demand due to the Earthquakes and Aftershocks

**Demand at any demand node is:**

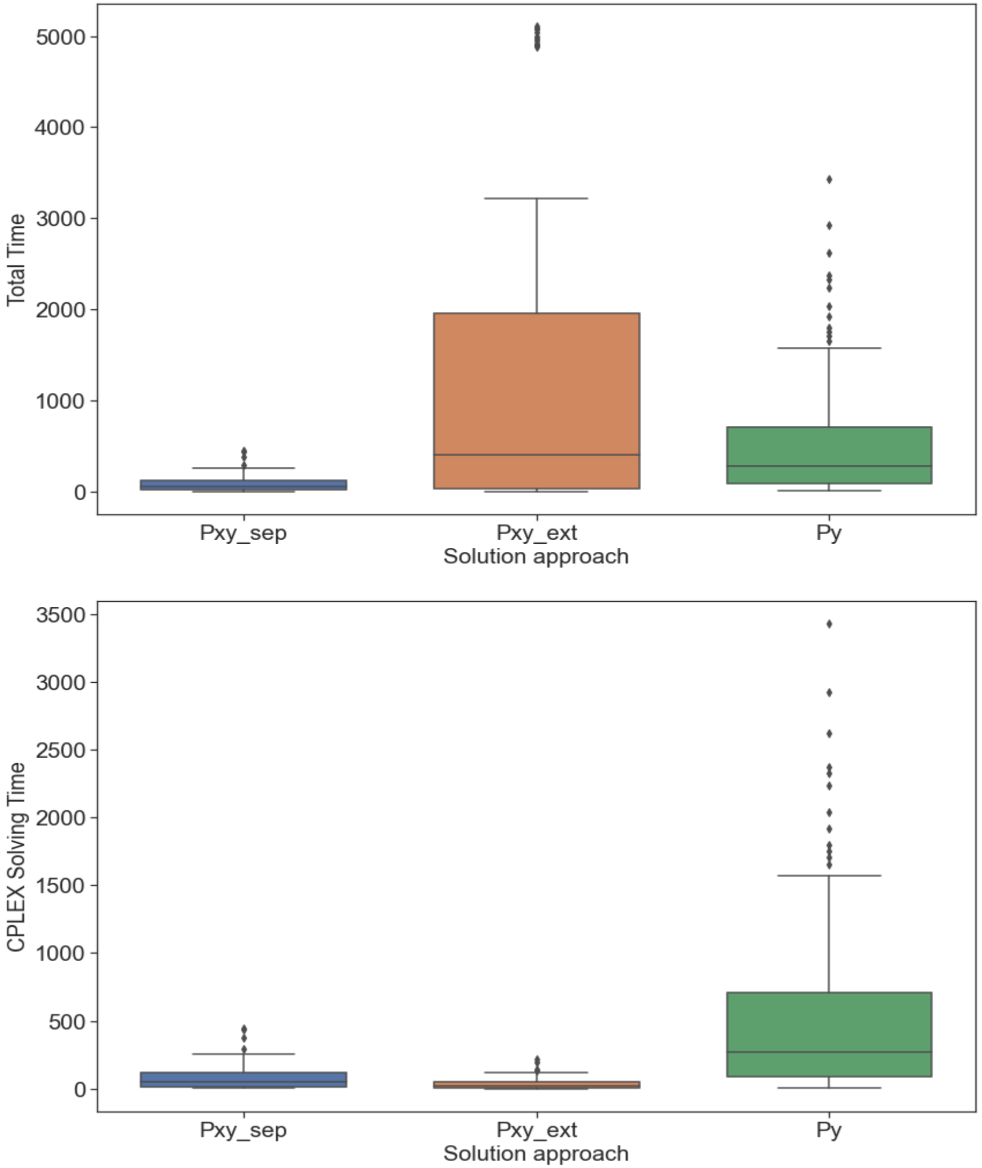
- Strictly increasing in the ***Magnitude*** of the Earthquake
- Strictly decreasing with the ***Distance*** from the Epicenter
- Strictly increasing to the ***Population*** of the Demand Node

$$\boldsymbol{Demand = k \cdot \frac{Population * Magnitude^{\alpha}}{Distance^{\beta}}}$$

*$k$, $\alpha$, and $\beta$ are calibrated using a regression model based on data from Turkey following the earthquake of February 2023*

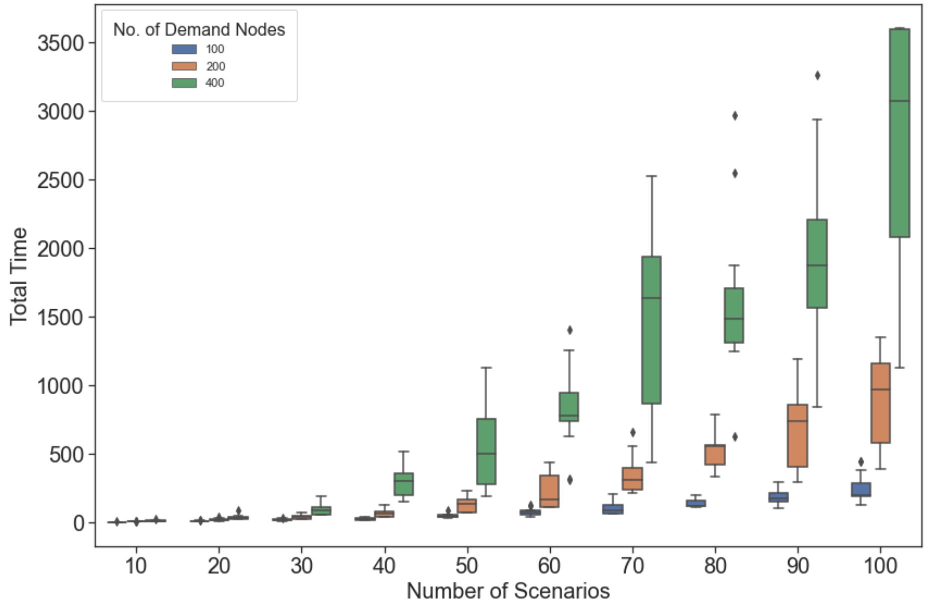
# Results

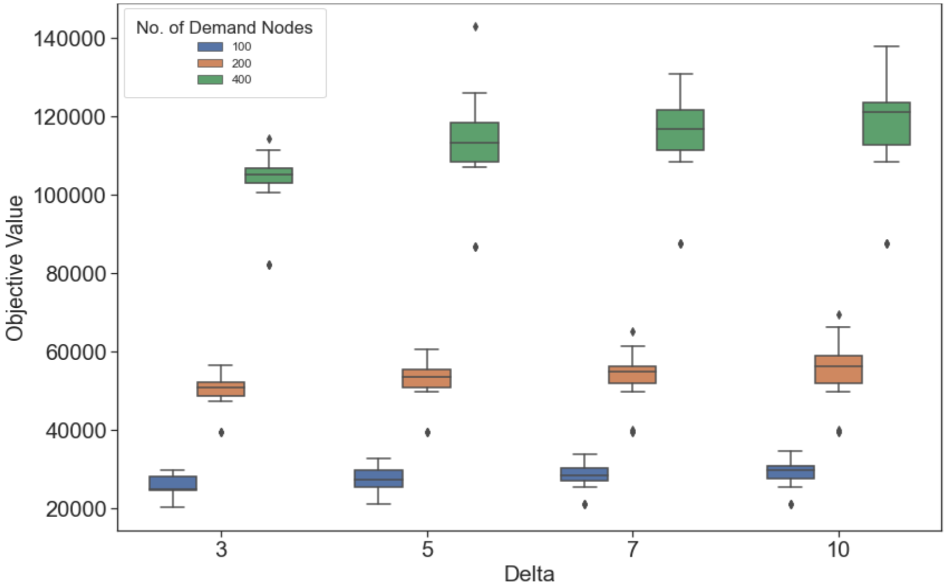
- Models were solved using CPLEX
- Initially, we solve only the Small instances to compare our models
- The « full enumeration » model could solve all instances with up to 20 main earthquakes and 40 aftershocks. Beyond that NO instance was solved for any values of N and Δ
- The solution approach $\mathbf{P_{xy}^{sep}}$, with **separation of scenarios** is the **best performing** one in terms of computational time and finding an optimal solution
- $P_{xy}^{ext}$ had the worst total time. It took a lot of time for building the models by CPLEX, but once built took the lowest time
- $P_y$ performance is in-between



# Results

- The separation approach was able to find a solution for all instances and **optimal solutions for 356 instances out of 360** (with a low gap for others)
- The solution time increases as the number of scenarios increases
- The solution time decreases for the separation model as Δ increases
- The objective value (allocation cost) increases with the value of Δ, particularly for instances with 400 demand nodes



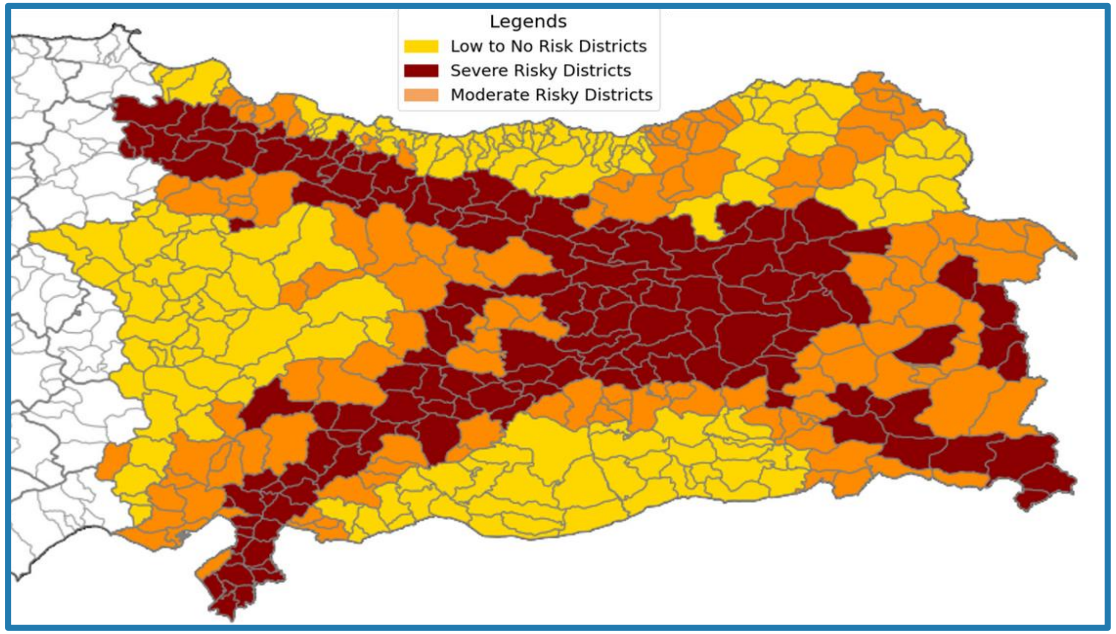



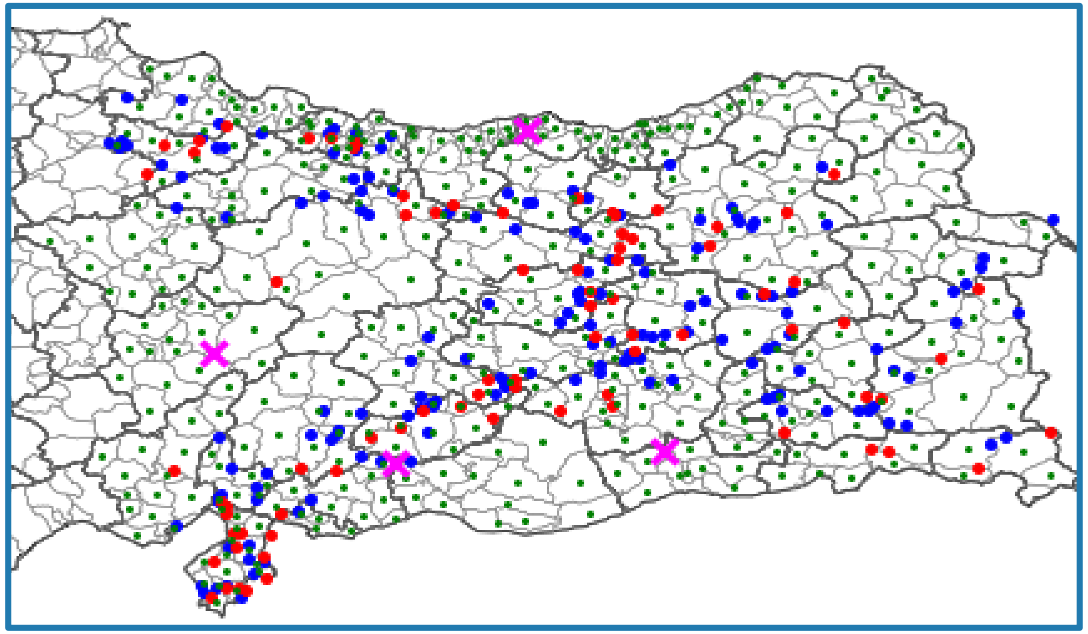
# Case Study on the Turkey-Syria Earthquake of February 2023

- Implement our robust model on Turkey for establishing warehouses
- Turkey lies at the border of three tectonic plates
- **269 earthquakes** between 1900 and 2023
- **20 earthquakes of magnitude greater than 7**
- February 2023 earthquake is the latest one

ESSEC BUSINESS SCHOOL

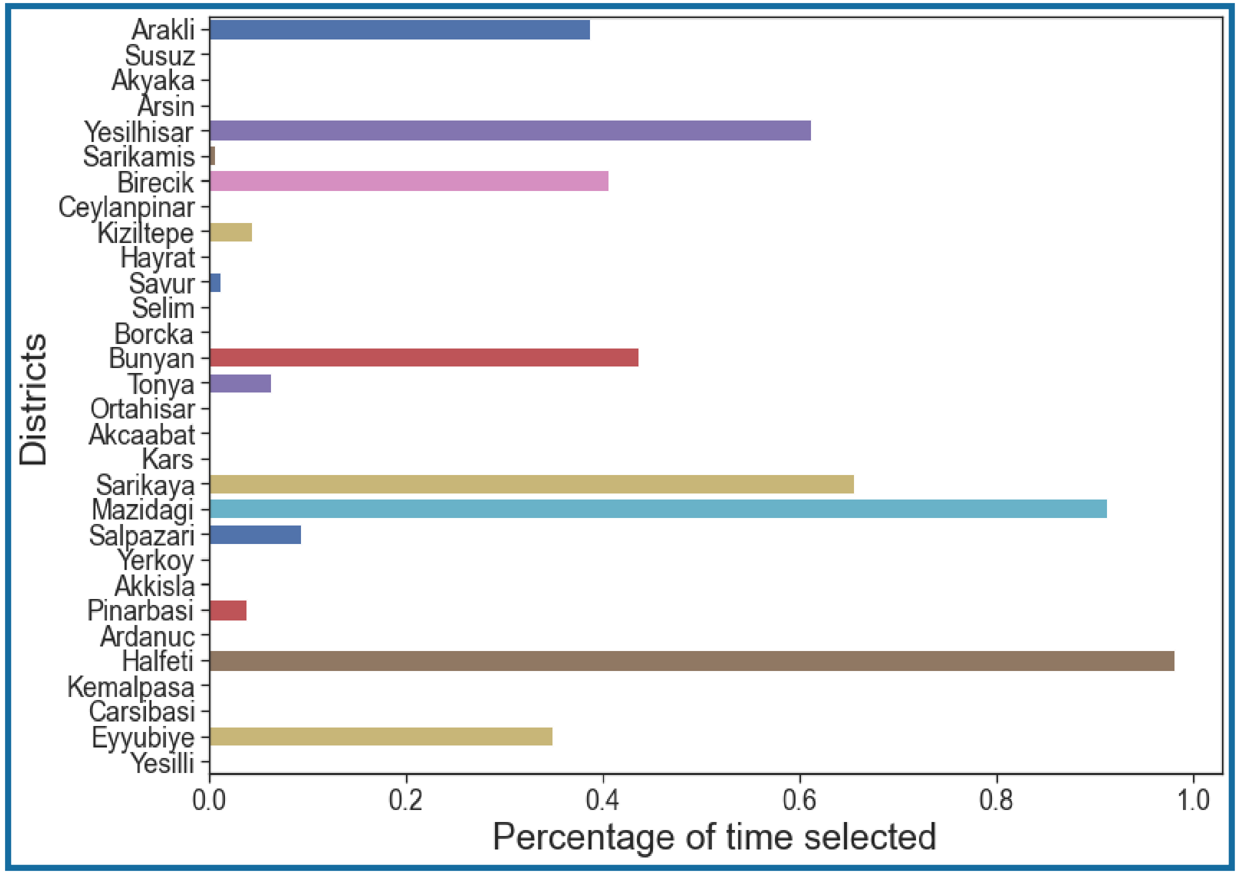
# Instances for Turkey



- Instances based on the earthquake hazard map by AFAD
- Red-Severely risky, orange- moderate risky, yellow- no to low risky areas
- Red circles- earthquake epicentres, blue circles- aftershock epicenters, pink crosses- facilities, green circles- demand nodes (420 district centers)
- 70% epicenters in the red region, 30% in the orange region

# Districts selected for constructing a warehouse




Some of the districts were selected more often than others:

- Halfeti- 98%
- Mazidagi- 91%
- Sarikaya- 66%
- Yesilhisar- 61%

ESSEC BUSINESS SCHOOL

# Comparison with a First-Stage Model (without Aftershocks) : is it worth modelling aftershocks?

$$
\begin{aligned}
\mathbf{P}_{\mathbf{xy}}^{\mathbf{StageI}}: \quad & \min \quad \theta \\
\text{subject to} \quad & \theta \geq \sum_{i \in \mathscr{D}} \sum_{j \in \mathscr{F}} t_{ij} d_{si}^{1} x_{ij} \qquad s \in \mathscr{S} \\
& \sum_{j \in \mathscr{F}} x_{ij} = 1 \qquad i \in \mathscr{D} \\
& y_j \geq x_{ij} \qquad i \in \mathscr{D},\ j \in \mathscr{F} \\
& 1 \leq \sum_{j \in \mathscr{F}} y_j \leq N \\
& \theta \geq 0, \quad x_{ij}, y_j \in \{0,1\} \qquad i \in \mathscr{D},\ j \in \mathscr{F}
\end{aligned}
$$

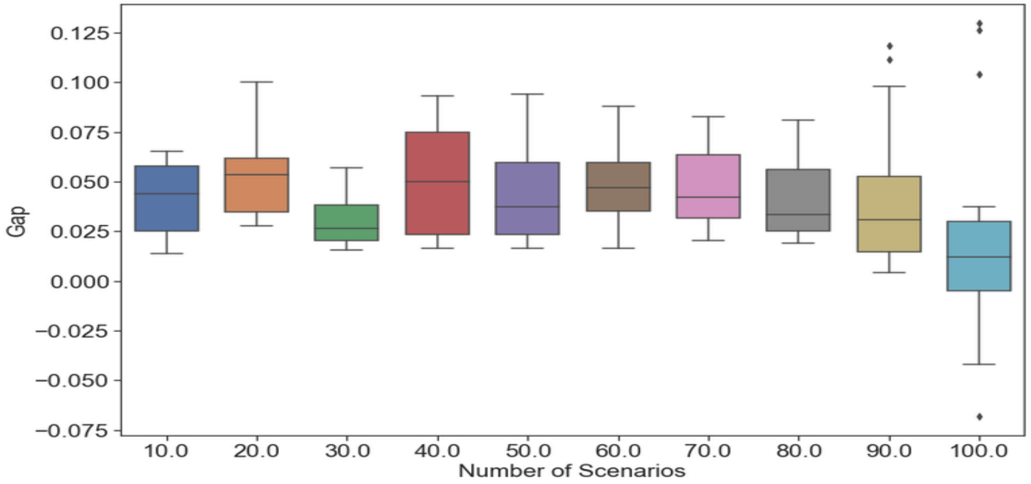
$$
\text{Gap} = \frac{\text{ROV}_1 - \text{ROV}_2}{\text{ROV}_2}
$$

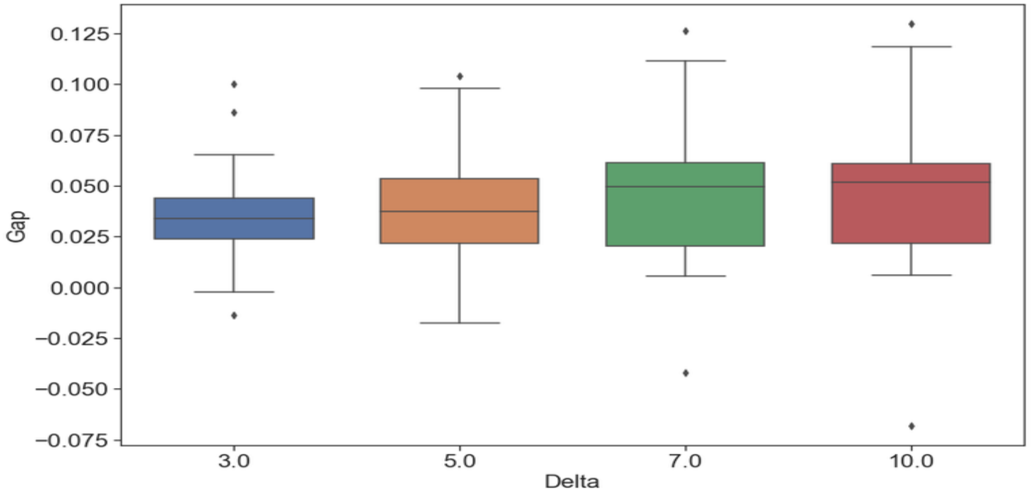
ESSEC BUSINESS SCHOOL

# Comparison with a First-Stage Model (without Aftershocks)

$$\text{Gap} = \frac{\text{ROV}_1 - \text{ROV}_2}{\text{ROV}_2}$$

- The gap goes over 12.5%
- Average gap is 4.5%



# Conclusions

- ***Robust Facility Location / SC network design*** – **Strategic planning**
- **<u>New</u> key feature for robust optimization:** binary choices of the Δ aftershocks for the 2nd-stage uncertainty set (instead of Γ coefficients of a constraint varying in « usual » RO ( ≠ Bertsimas & Sim 2004)
- The model with ***full enumeration of scenarios (Model 1) gets quickly intractable***
- For ***small-size*** instances, the ***B&C separation algorithm (Model 2) and the extended formulation (Model 3)*** perform similarly (up to 30 major earthquakes, 100 aftershocks, 200 demand nodes)
- As the ***instance size increases, the B&C separation algorithm (Model 2) is the most efficient***
- The model with y variables + separation (Model 4) outperforms the extended formulation (Model 3) as the instance size increases
- The models **except Model 2** are ***highly sensitive to the number of aftershocks***
- Case Study on the Turkey Gaziantep Earthquake of 2023
- Not modelling aftershocks can give a gap on objective value up to 12.5%
- ***Possible extension: capacitated version*** (creates differentiation of assignments $x_{ij}$ over the two stages)

# Some References


1. Balcik, B., & Beamon, B. M. (2008). Facility location in humanitarian relief. *International Journal of logistics*, *11*(2), 101-121.
2. Salman, F. S., & Yücel, E. (2015). Emergency facility location under random network damage: Insights from the Istanbul case. *Computers & Operations Research*, *62*, 266-281.
3. Erbeyoğlu, G., & Bilge, Ü. (2020). A robust disaster preparedness model for effective and fair disaster response. *European Journal of Operational Research*, *280*(2), 479-494.
4. Elçi, Ö., & Noyan, N. (2018). A chance-constrained two-stage stochastic programming model for humanitarian relief network design. *Transportation research part B: methodological*, *108*, 55-83.
5. Lin, Y. H., Batta, R., Rogerson, P. A., Blatt, A., & Flanigan, M. (2012). Location of temporary depots to facilitate relief operations after an earthquake. *Socio-Economic Planning Sciences*, *46*(2), 112-123.
6. Lu, C. C., & Sheu, J. B. (2013). Robust vertex p-center model for locating urgent relief distribution centers. *Computers & Operations Research*, *40*(8), 2128-2137.
7. Rezaei-Malek, M., Tavakkoli-Moghaddam, R., Zahiri, B., & Bozorgi-Amiri, A. (2016). An interactive approach for designing a robust disaster relief logistics network with perishable commodities. *Computers & industrial engineering*, *94*, 201-215.
8. Alizadeh, M., Amiri-Aref, M., Mustafee, N., & Matilal, S. (2019). A robust stochastic Casualty Collection Points location problem. *European Journal of Operational Research*, *279*(3), 965-983.
9. Balcik, B., Silvestri, S., Rancourt, M. È., & Laporte, G. (2019). Collaborative prepositioning network design for regional disaster response. *Production and Operations Management*, *28*(10), 2431-2455.
10. Paul, J. A., & Wang, X. J. (2019). Robust location-allocation network design for earthquake preparedness. *Transportation research part B: methodological*, *119*, 139-155.
11. Paul, J. A., & MacDonald, L. (2016). Location and capacity allocations decisions to mitigate the impacts of unexpected disasters. *European Journal of Operational Research*, *251*(1), 252-263.

Thank you for your attention :)

Questions?