Optimization and Data Analytics Tools for Addressing COVID-19 Related Problems

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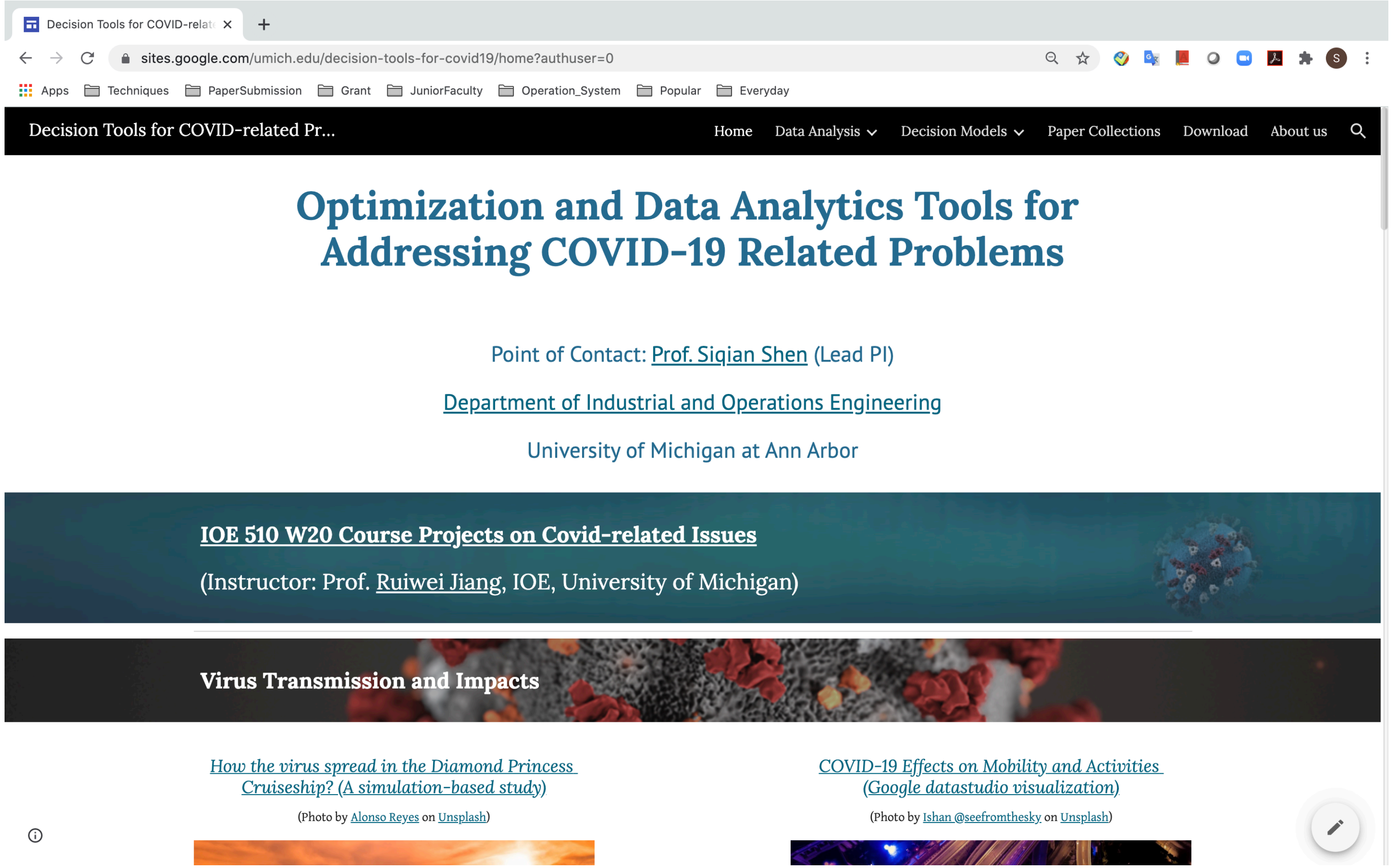
Outline

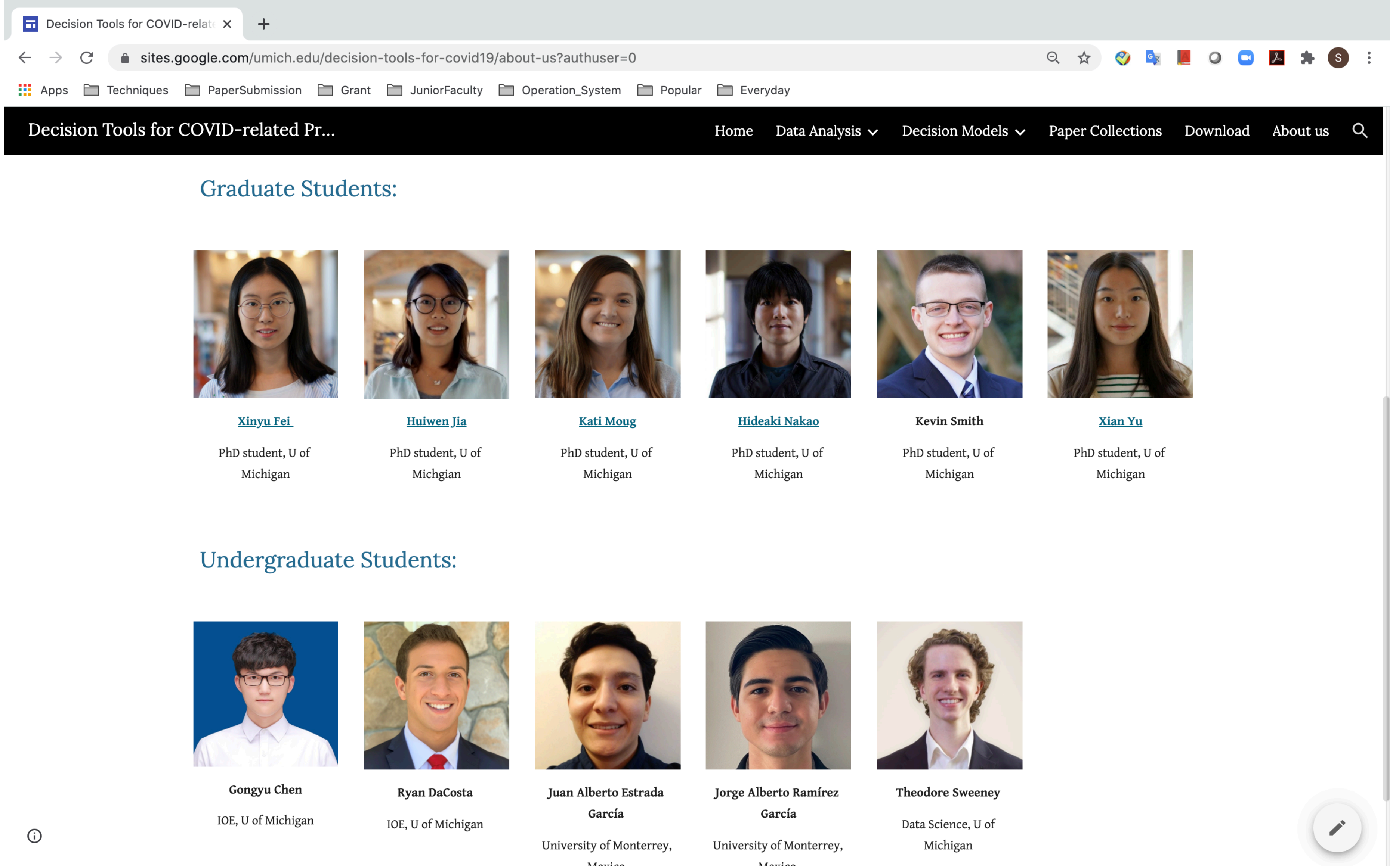
- ❑Introduction
- ❑COVID-19 and Mobility
- ❑Business Reopening / Lockdown
- ❑Redesign Public Transit Systems
- ❑Conclusion

A Collection of Problems and Solutions

https://sites.google.com/umich.edu/decision-tools-for-covid19/



Team



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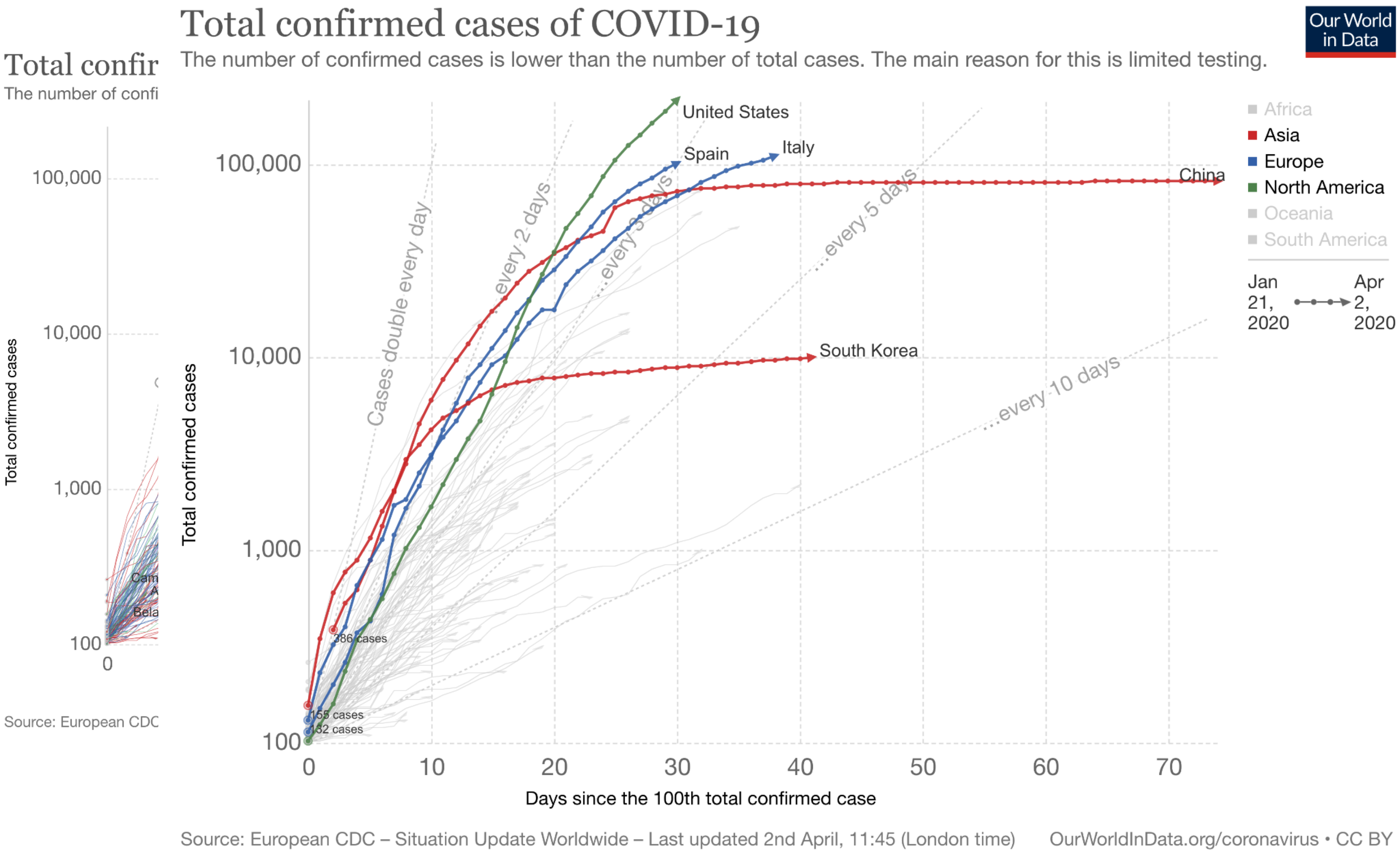
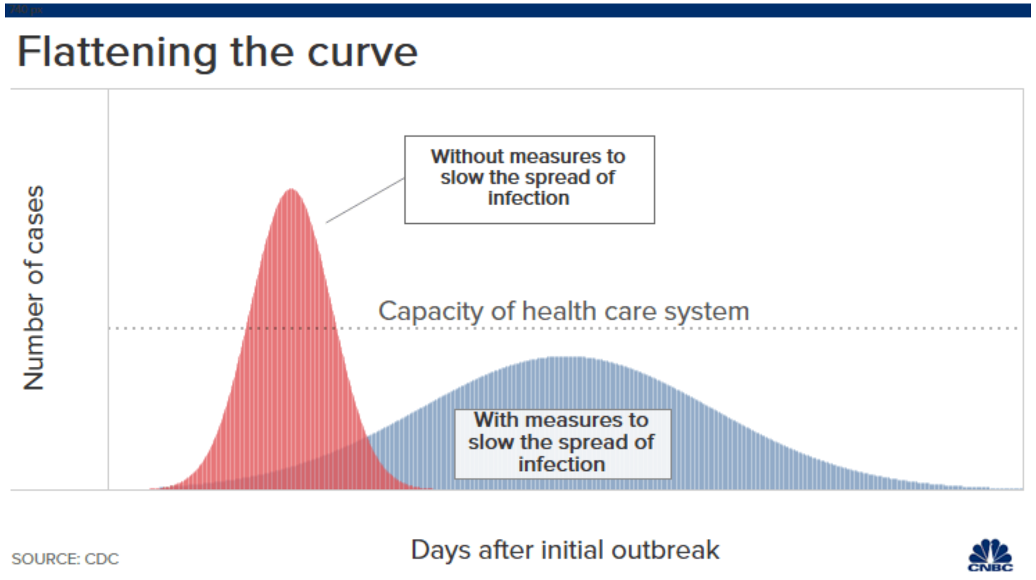
What Data Analytics Can Show Us?



From Data to Actions, to Solutions

- How to ``flatten the curve?”
- What problems in epidemic **prevention**, **intervention**, **control** and **recovery phases** need to be solved?
- How Optimization and System Engineering tools can help to tackle COVID-related problem?



A Summary and Literature Review in 03/20

http://www-personal.umich.edu/~siqian/docs/or-ie-fighting-covid19_v1.pdf

From Data to Actions, From Observations to Solutions

A Summary of Operations Research and Industrial Engineering Tools for Fighting COVID-19

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Latest Update on March 24, 2020

Operations Research and Industrial Engineering (OR & IE) approaches are widely used and play important roles in improving the design and operations of many standard corporate activities such as supply chain management, job/staff scheduling, vehicle routing, facility location, and resource allocation. In the midst of the COVID-19 pandemic, policymakers, companies, community workers and individual households have been designing new systems and procedures to fight the virus. Many problems related to optimizing these systems and their operations can be tackled by extending the traditional OR & IE approaches with new objectives, constraints, and input data. The purpose of this document is to **summarize potential scenarios one may encounter during the prevention, disease control, intervention and recovery phases during COVID-19 outbreaks, and point out the OR & IE models that can be applied for solving the related problems**. We are not medical experts and thus will not focus on the drug & vaccine discovery, nor analyzing the disease transmission rate and its spread patterns. Instead, we consider decisions made by multiple stakeholders that can prepare for rare but catastrophic events such as the COVID-19 pandemic, can better inform the public to perform

A Summary of Operations Research and Industrial Engineering Tools for Fighting COVID-19

Siqian Shen
Mar 24 · 6 min read

Operations Research and Industrial Engineering (OR & IE) approaches are widely used and play important roles in improving the design and operations of many standard corporate activities such as supply chain management, job/staff scheduling, vehicle routing, facility location, and resource allocation. In the midst of the COVID-19 pandemic, policymakers, companies, community workers and individual households have been designing new systems and procedures to fight the virus. Many problems related to optimizing these systems and their operations can be tackled by extending the traditional OR & IE approaches with new objectives, constraints, and input data. The purpose of this document is to **summarize potential scenarios one may encounter during the prevention, disease control, intervention, and recovery phases during COVID-19 outbreaks, and point out the OR & IE models that can be applied for solving the related problems**. We are not medical experts and thus will

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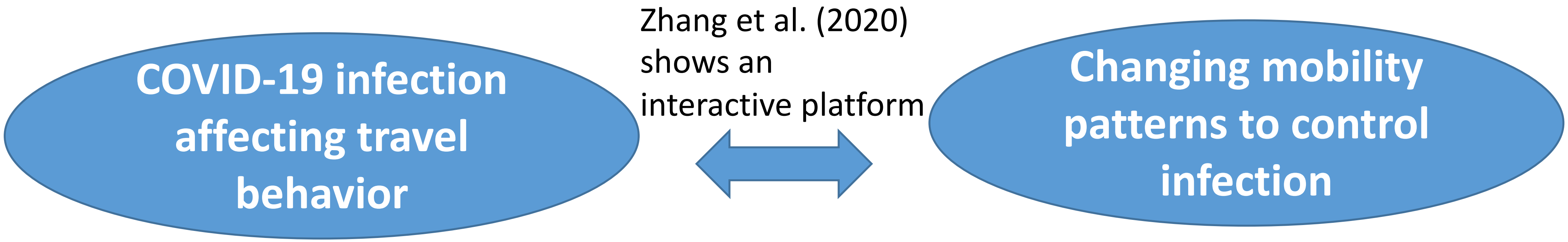
Relations of COVID-19 and Mobility



- Warren and Skillman (2020), Bonaccors et al. (2020), Coven and Gupta (2020) analyze how human mobility patterns change in the US, Italy, and NYC, dependent on their COVID-19 infection severity, respectively.
- Kraemer et al. (2020) study mobility reduction to control virus spread in China.
- Prem et al. (2020) study the effect of social mixing reduction to control virus spread via SEIR model.
- Badr et al. (2020) study social distancing in the US to control virus.

Our Data and Analysis

- **Data sources**: Google Community Mobility Reports (https://www.google.com/covid19/mobility/)
- Data include relative changes of travel from/to workplaces, retail, residential, grocery and pharmacy, etc.) from 02/15 to 08/21 in 2020.
- Time-series decomposition model: for each time t:

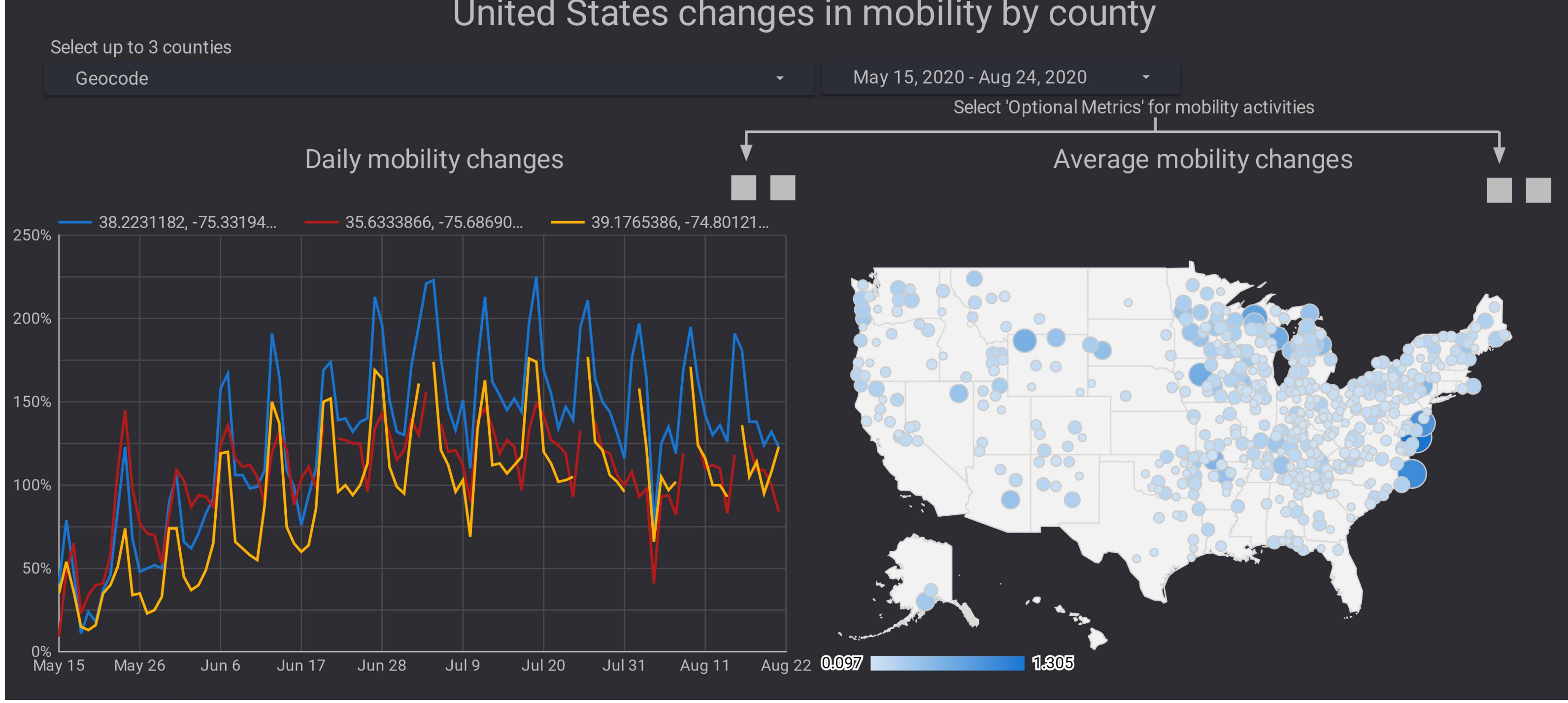
$$X_t = T_t + S_t + I_t$$

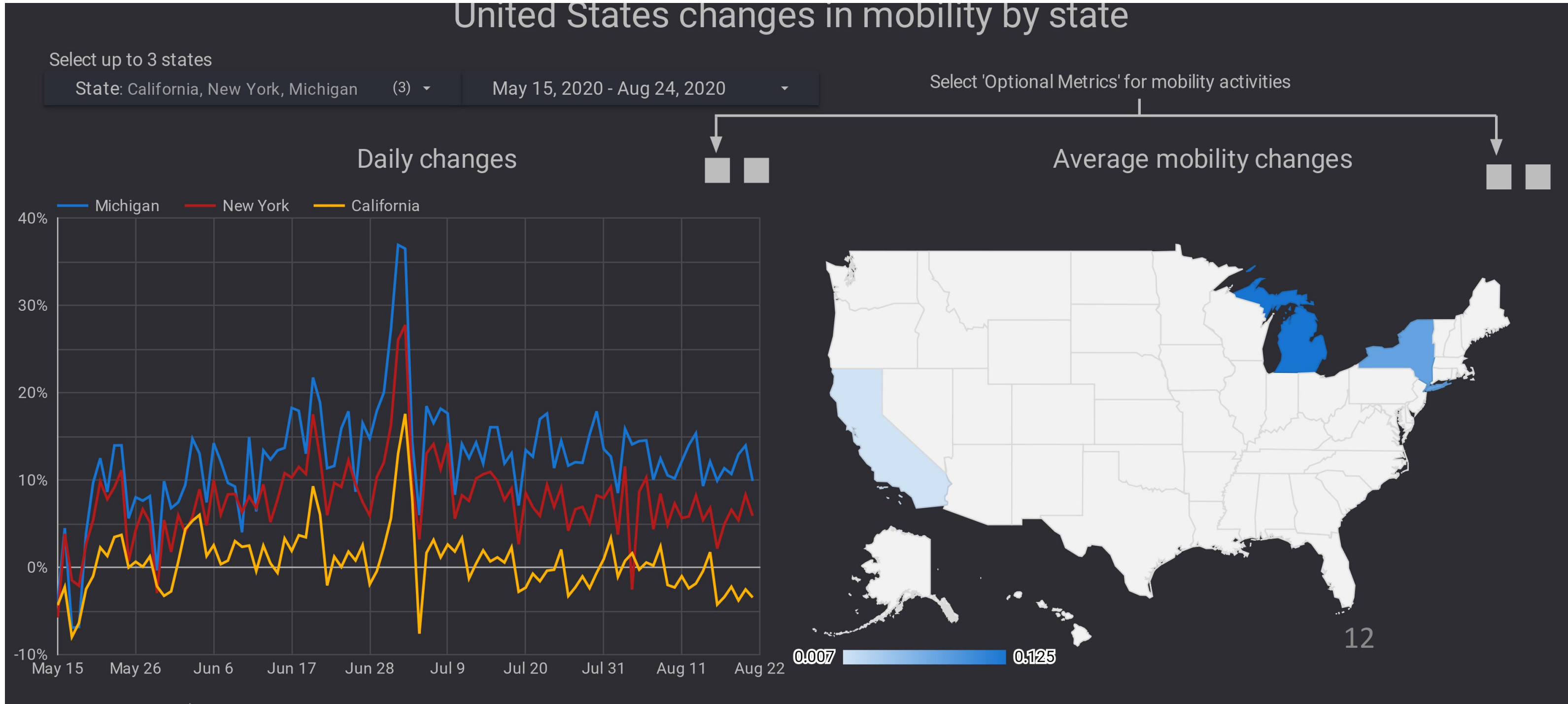
where T_t: trend component, S_t: seasonal component, I_t: irregular component.

- Use seasonal_decompose function from Python package statsmodels.

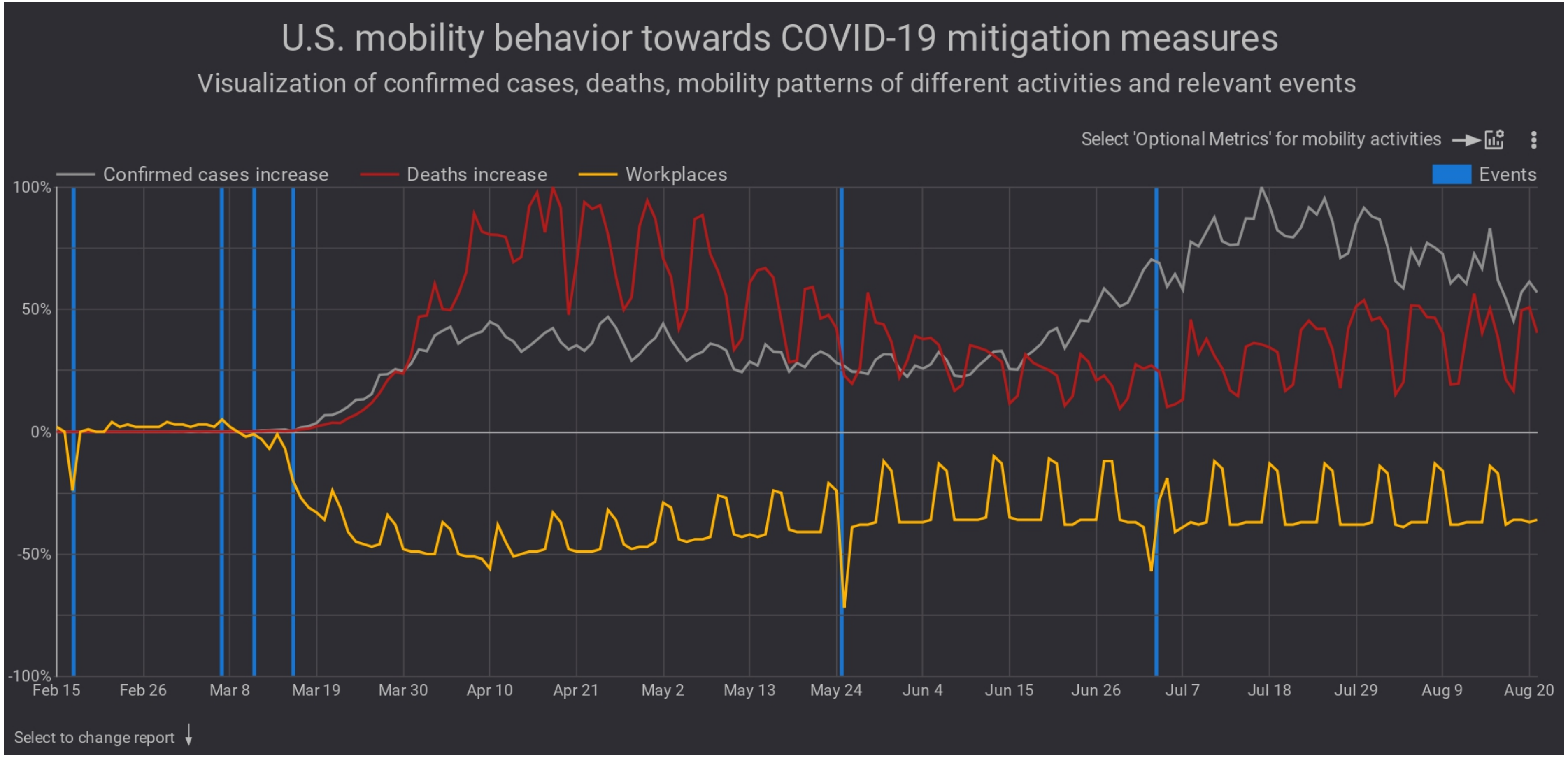
Data Dashboard I

- US overall mobility changes by County or by State.



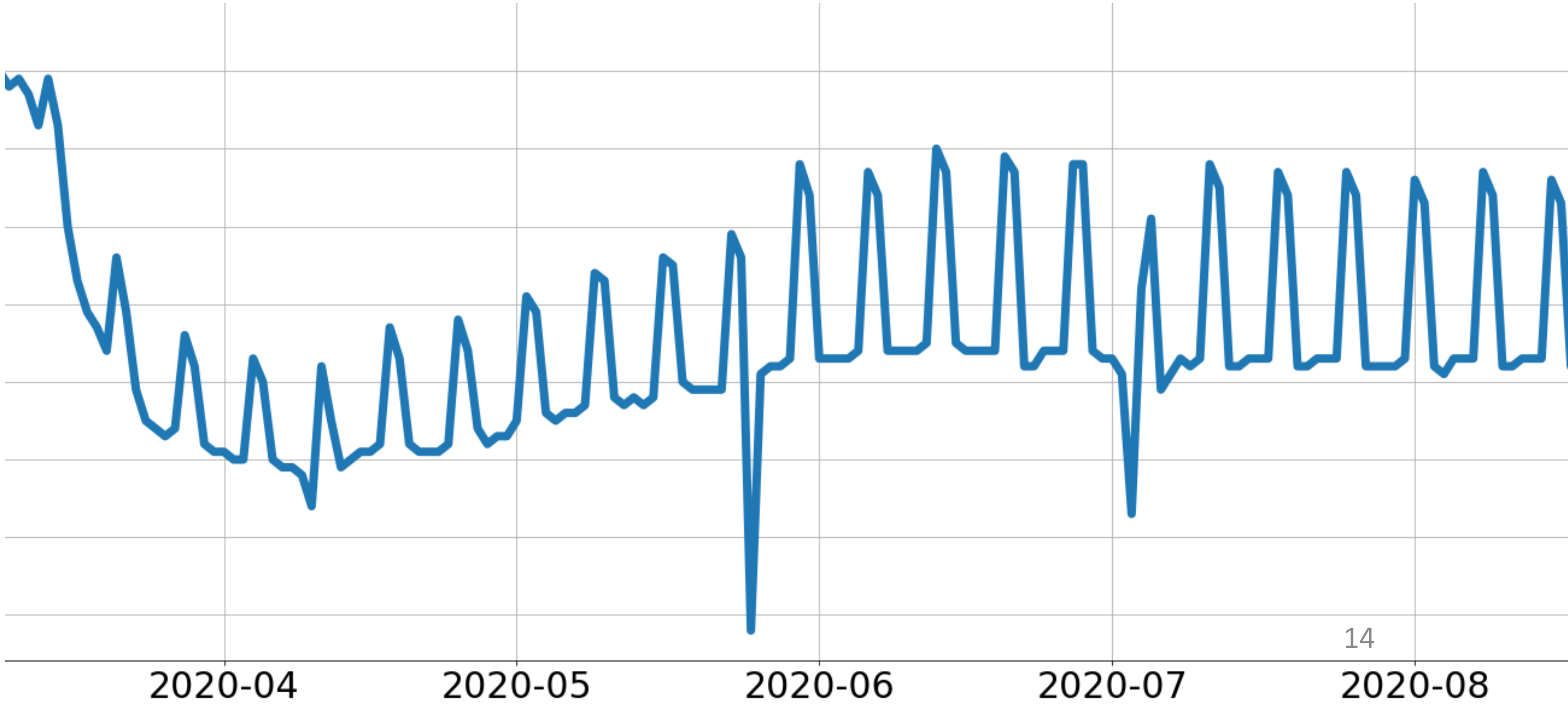


Data Dashboard II



Results

- US mobility changes in travels to grocery or pharmacy (up figure) and to workplace (down figure)



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Lockdown – A Knapsack Problem

- Select facilities to close and populations to quarantine/get vaccination

$$\text{DPEC-B}: \quad \min_{x,z} \quad \sum_{j\in\mathcal{F}} \rho_j \left(\sum_{i\in\mathcal{P}} p_{ij}(1-h_i)\left(r_i^{AV} z_i + r_i^{BV}(1-z_i)\right)\right)(1-x_j) \tag{2a}$$

$$\text{s.t.} \quad \sum_{i\in\mathcal{P}} c_i z_i \leqslant B_z \tag{2b}$$

$$\sum\nolimits_{j\in\mathcal{F}} d_j x_j \leqslant B_x \tag{2c}$$

$$x_j \in \{0,1\} \quad \forall j \in \mathcal{F} \qquad z_i \in \{0,1\} \quad \forall i \in \mathcal{P}. \tag{2d}$$

- Such a static model can be extended to a dynamic setting if we update the virus spread information periodically and make updated lockdown decisions sequentially.

Ref: Deng, Y., Shen, S., & Vorobeychik, Y. (2013). Optimization methods for decision making in disease prevention and epidemic control. Mathematical Biosciences, 246(1), 213-227.

To Build A Quarantine Model

- **What we know (Input Data)**

  A network with nodes representing population groups or facilities and edges representing how they are connected.

- **What we need to decide (Decisions)**
  - Identify the most critical nodes (e.g., facilities visited by most people daily or workers such as doctors who may infect many vulnerable populations if they are sick)
- **What are the goals (Objective)**
  - Provide extra protection for the most critical nodes during their normal operations or quarantine them if they are infected

An Interdiction Model for Disconnecting a Network

- Decide which node(s) to delete (quarantine) to maximize network disconnectivity.

$$\max\ \eta(x, y) - \frac{1}{n}\sum_{i\in\mathcal{V}}(1 - x_i)$$

$$\text{s.t.}\ \sum_{i\in\mathcal{V}}(1 - x_i) \le B$$

$$x_i + x_j - 1 \le y_{ij}, \quad y_{ij} \le x_i,\ y_{ij} \le x_j\ \forall(i, j) \in \mathcal{E}$$

$$x_i \in \{0, 1\} \quad \forall i \in \mathcal{V}$$

$$0 \le y_{ij} \le 1 \quad \forall(i, j) \in \mathcal{E}.$$

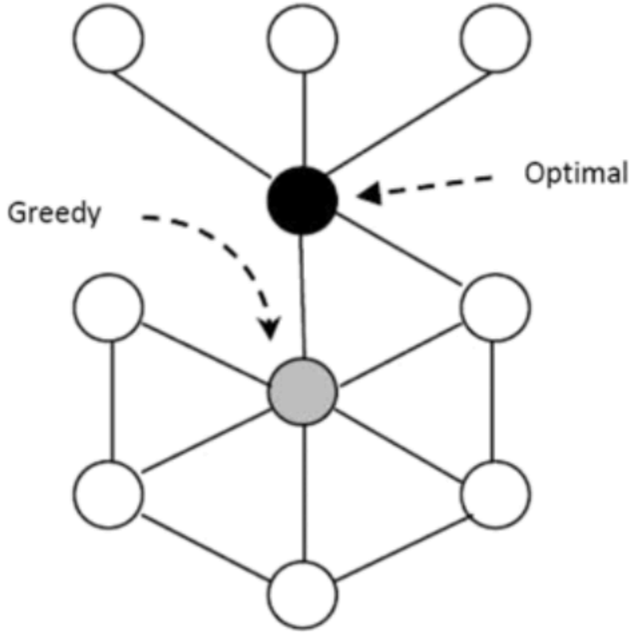
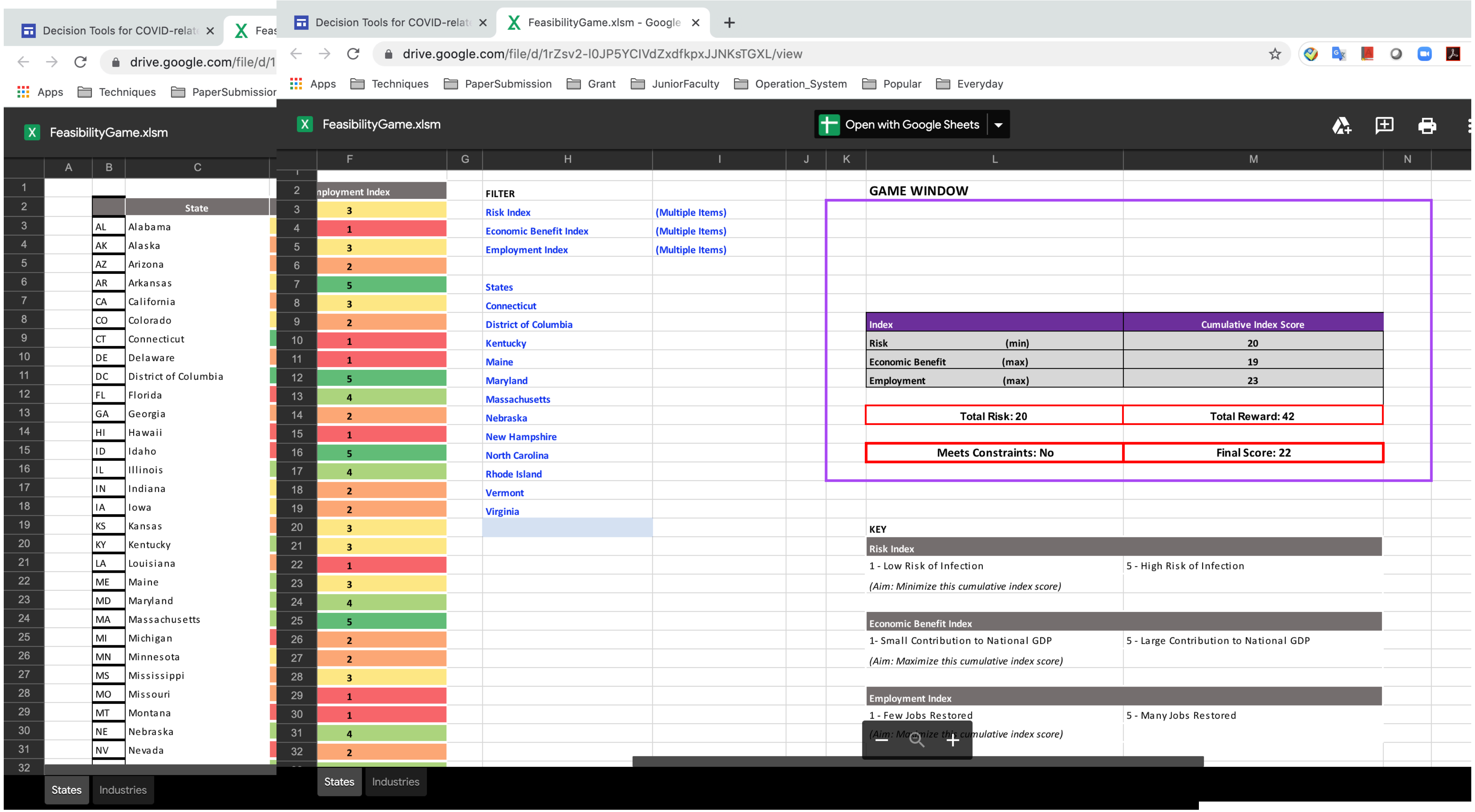


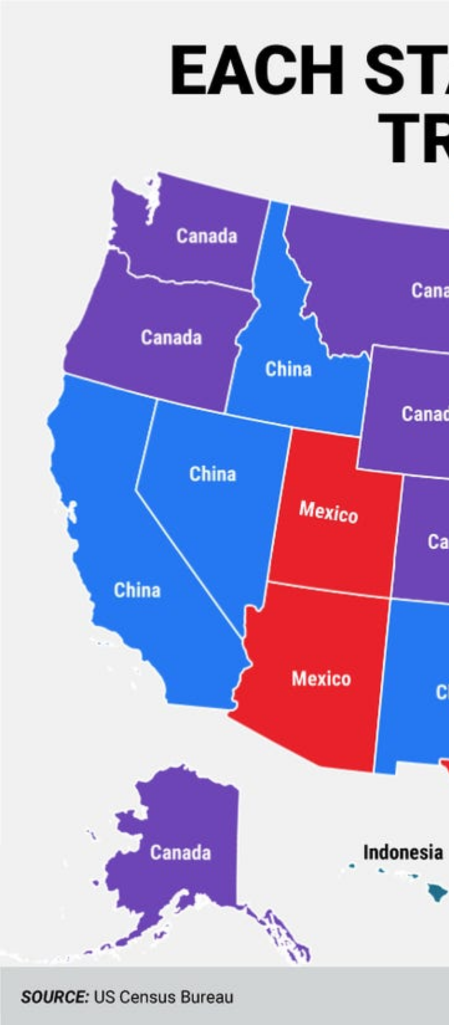
Fig. 1. Suboptimality of the greedy algorithm in MaxNum for $B = 1$.

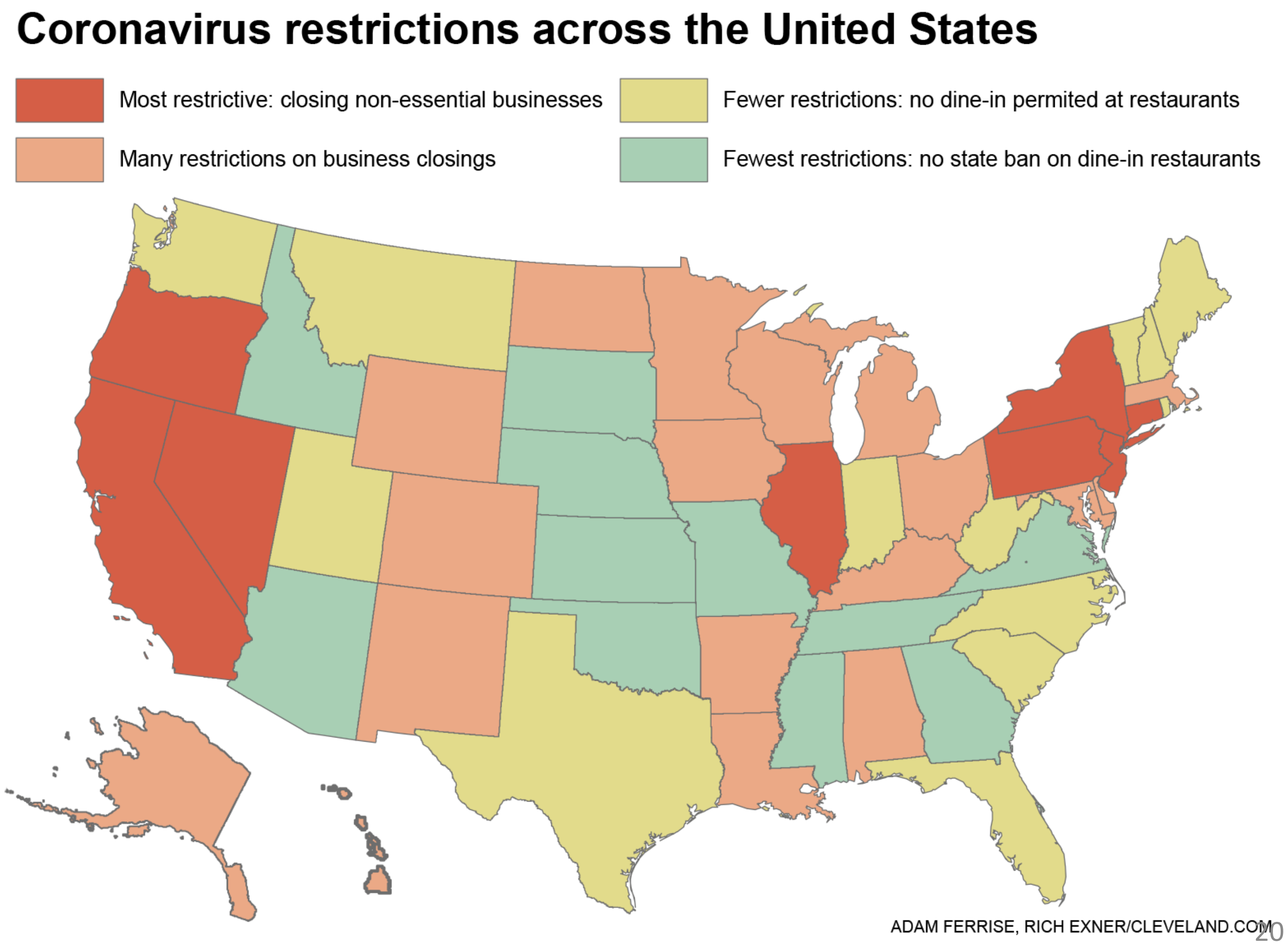
Ref: Shen, S., Smith, J. C., & Goli, R. (2012). Exact interdiction models and algorithms for disconnecting networks via node deletions. Discrete Optimization, 9(3), 172-188.

A Reopen Game – A Knapsack View



Consider Business Trade Across States/Countries





A Network-based Optimization Model

- I: set of regions; J: set of industries; $\{1, \dots, T\}$: decision period for open or close certain businesses.
- $G_j(V, E_j)$ – the business type $j's$ trading network.
- α_{it} and β_{it} – baseline infection/recover rate in region i and period t (if no business is open).
- $\tilde{b}_{ijt}$: random # of new infections in region i, period t if reopen business j.
- Decisions:
  - x_{ijt} - whether to reopen business j in region i, period t.
  - $y_{i'i''t}$- amount of business trading between regions i' and i'' in time t.
  - z_{ijt} - local trading of products related to business j in region i, period t.
  - a_{it} - # of infections in region i, period t.

A Network-based Optimization Model

$$\max \quad \sum_{t=2}^{T+1}\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}} \delta_{ijt}x_{ijt} + (1-\eta)\left(\sum_{t=1}^{T+1}\sum_{j\in\mathcal{J}}\sum_{e_j\in E_j} p_{e_jt}y_{e_jt} + \sum_{t=1}^{T+1}\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}} q_{ijt}z_{ijt}\right) - \eta\sum_{t=1}^{T+1}\sum_{i\in\mathcal{I}} w_{it}a_{it} \tag{1a}$$

$$\text{s.t.} \quad \sum_{e\in\delta_j^+(i)} y_{et} + z_{ijt} \le \tilde{R}_{ijt}x_{ijt},\ \forall i\in\mathcal{I},\ \forall j\in\mathcal{J},\ t=1,\cdots,T+1 \tag{1b}$$

$$\sum_{e\in\delta_j^-(i)} y_{et} + z_{ijt} \le \tilde{D}_{ijt}x_{ijt},\ \forall i\in\mathcal{I},\ \forall j\in\mathcal{J},\ t=1,\cdots,T+1 \tag{1c}$$

$$\sum_{j\in\mathcal{J}} s_{ijt}(1-x_{ijt}) \le v_{it},\ \forall i\in\mathcal{I},\ t=2,\cdots,T+1 \tag{1d}$$

$$a_{it+1} \ge a_{it} + \alpha_{it}a_{it} + \sum_{j\in\mathcal{J}} \tilde{b}_{ijt}x_{ijt},\ \forall i\in\mathcal{I},\ t=1,\cdots,T_0 \tag{1e}$$

$$a_{it+1} \ge a_{it} + \alpha_{it}a_{it} + \sum_{j\in\mathcal{J}} \tilde{b}_{ijt}x_{ijt} - \beta_{it-T_0}a_{it-T_0},\ \forall i\in\mathcal{I},\ t=T_0+1,\cdots,T \tag{1f}$$

$$a_{i1} = a_i^{\text{init}},\ \forall i\in\mathcal{I} \tag{1g}$$

$$a_{it} \le c_{it},\ \forall i\in\mathcal{I},\ t=2,\cdots,T+1 \tag{1h}$$

$$h_{it}a_{it} \le d_{it},\ \forall i\in\mathcal{I},\ t=2,\cdots,T+1 \tag{1i}$$

$$f_{it} + \sum_{j\in\mathcal{J}} g_{ijt}x_{ijt} \le l_{it},\ \forall i\in\mathcal{I},\ t=2,\cdots,T+1 \tag{1j}$$

$$m_{it} + \sum_{j\in\mathcal{J}} n_{ijt}x_{ijt} \le u_{it},\ \forall i\in\mathcal{I},\ t=2,\cdots,T+1 \tag{1k}$$

$$y_{e_jt}\ge 0,\ z_{ijt}\ge 0,\ a_{it}\ge 0,\ \forall i\in\mathcal{I},\ \forall j\in\mathcal{J},\ \forall e_j\in E_j,\ \forall t=1,\cdots,T+1 \tag{1l}$$

$$x_{ijt+1} \le x_{ijt} + 1 - x_{ij}^{\text{init}},\ \forall i\in\mathcal{I},\ j\in\mathcal{J},\ t=1,\cdots,T+1 \tag{1m}$$

$$x_{ijt+1} \ge x_{ijt} - x_{ij}^{\text{init}},\ \forall i\in\mathcal{I},\ j\in\mathcal{J},\ t=1,\cdots,T+1 \tag{1n}$$

$$x_{ij1} = x_{ij}^{\text{init}},\ \forall i\in\mathcal{I},\ \forall j\in\mathcal{J} \tag{1o}$$

$$x_{ijt}\in\{0,1\},\ \forall i\in\mathcal{I},\ \forall j\in\mathcal{J},\ t=1,\cdots,T+1 \tag{1p}$$

→ Bound the amount of business trading and product sales based on reopening strategies.

→ Bound the number of lockdown activities.

→ Update infection level in future period based on current infection and business reopening.

→ Medical resource capacity on infection.

→ Bound the number of reopening activities.

→ Relationship between reopening & lockdown decisions over sequential periods.

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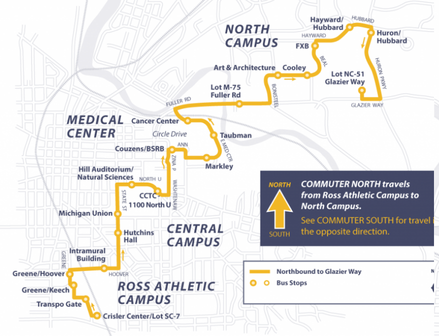
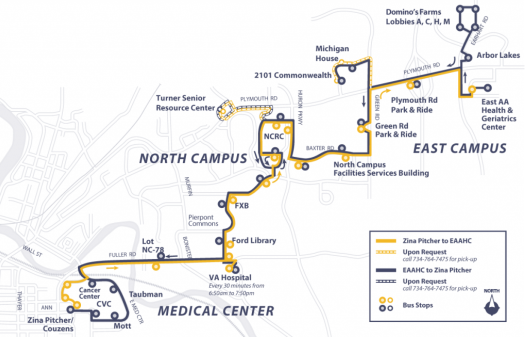
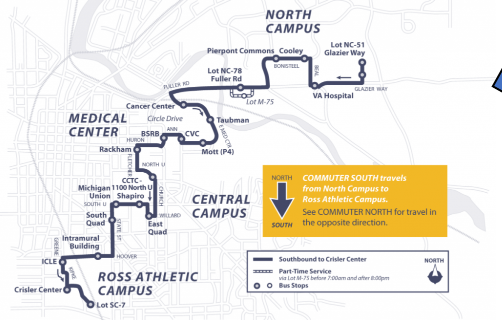
University of Michigan Campus Bus Route and Schedule Redesign

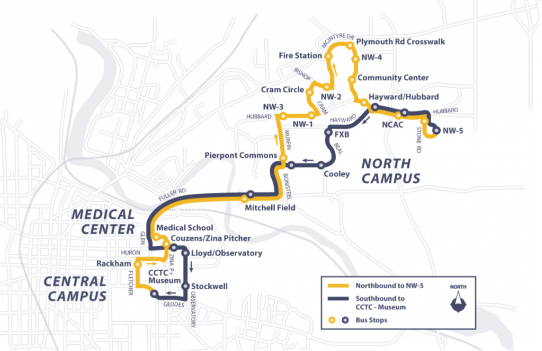
Hub-and-Spoke Design

Key idea: (i) shorten existing long routes to increase overall bus capacity utilization and frequency; (ii) consolidate bus stops to reduce the # of stops and shorten loading/unloading time.

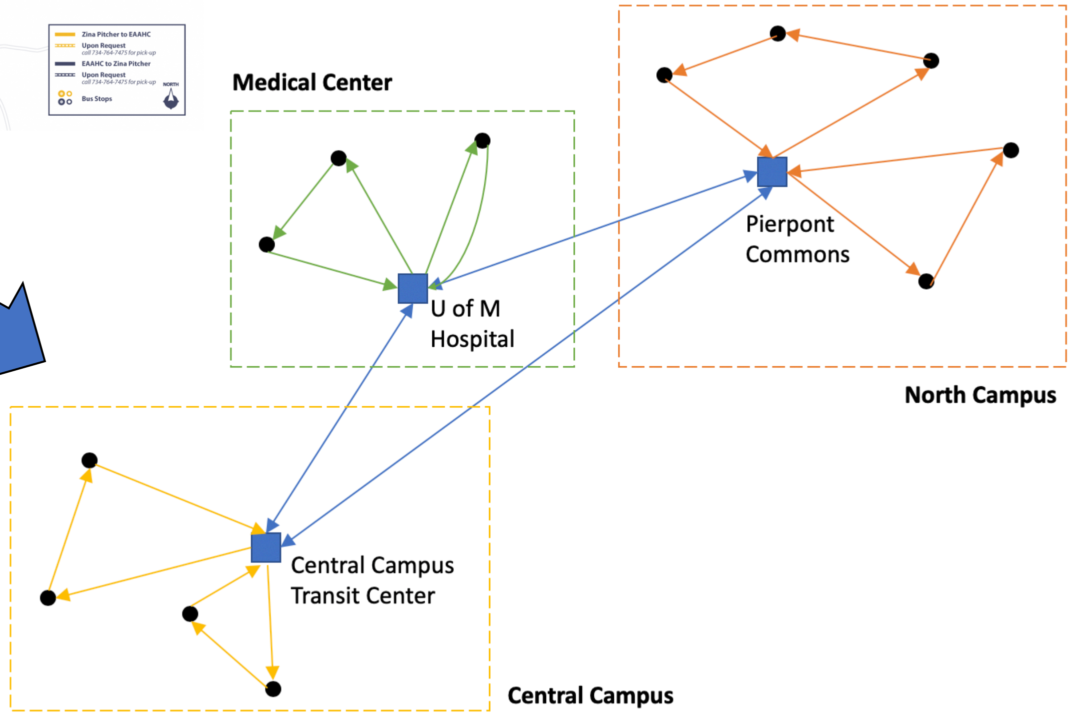








Hub-and-Spoke System

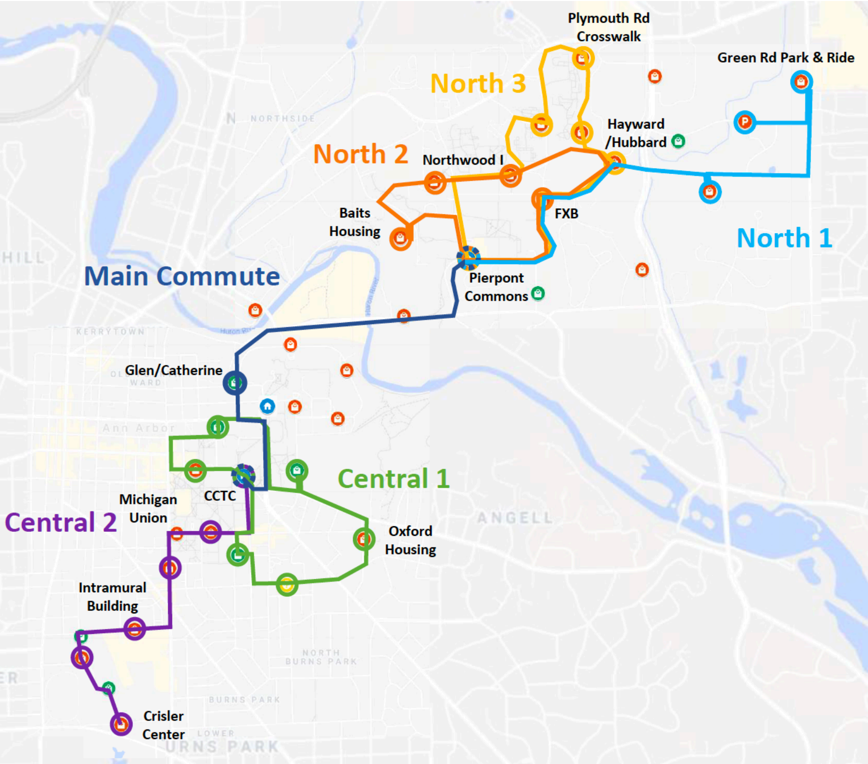


Optimize Bus Stops and Routes

$$
\begin{aligned}
\min \quad & \sum_{j\in J} c_j x_j + \sum_{j\in J}\left(\sum_{i\in I} t_{\text{depot},i} u^j_{i,1} + \sum_{k=1}^{|K|-1} \sum_{i_1,i_2\in I\cup\{\text{depot}\}} t_{i_1,i_2} z^j_{i_1,i_2,k} + \sum_{i\in I} t_{i,\text{depot}} u^j_{i,K}\right) && \text{(1a)}\\
\text{s.t.} \quad & \sum_{j\in J} y_{ij} = 1,\ \forall i\in I, && \text{(1b)}\\
& y_{ij} \le x_j,\ \forall i\in I,\ j\in J, && \text{(1c)}\\
& \sum_{k\in K} u^j_{i,k} = y_{ij},\ \forall i\in I,\ j\in J, && \text{(1d)}\\
& \sum_{i\in I} u^j_{i,k} + u^j_{\text{depot},k} = x_j,\ \forall k\in K,\ j\in J, && \text{(1e)}\\
& \sum_{i\in I} u^j_{i,k+1} \le \sum_{i\in I} u^j_{i,k},\ \forall k=1,\ldots,|K|-1,\ j\in J, && \text{(1f)}\\
& z^j_{i_1,i_2,k} \le u^j_{i_1,k},\ \forall i_1,i_2\in I\cup\{\text{depot}\},\ k=1,\ldots,|K|-1,\ j\in J, && \text{(1g)}\\
& z^j_{i_1,i_2,k} \le u^j_{i_2,k+1},\ \forall i_1,i_2\in I\cup\{\text{depot}\},\ k=1,\ldots,|K|-1,\ j\in J, && \text{(1h)}\\
& z^j_{i_1,i_2,k} \ge u^j_{i_1,k} + u^j_{i_2,k+1} - 1,\ \forall i_1,i_2\in I\cup\{\text{depot}\},\ k=1,\ldots,|K|-1,\ j\in J. && \text{(1i)}\\
& x_j\in\{0,1\},\ y_{ij}\in\{0,1\},\ u^j_{i,k}\in\{0,1\},\ \forall i\in I,\ k\in K,\ j\in J. && \text{(1j)}
\end{aligned}
$$

Key approach: We minimize # of routes we use to cover all selected stops and also the total travel time of all routes. We ensure: (i) all current stops are either selected or within 5min walking to a selected one; (ii) each route visits their assigned bus stops one by one; (iii) each route returns to their hub after visiting all stops assigned; (iv) trip time on any route <= 15 minutes. (We modify and improve the solution via simulation.)

Design Bus Schedules on New Routes

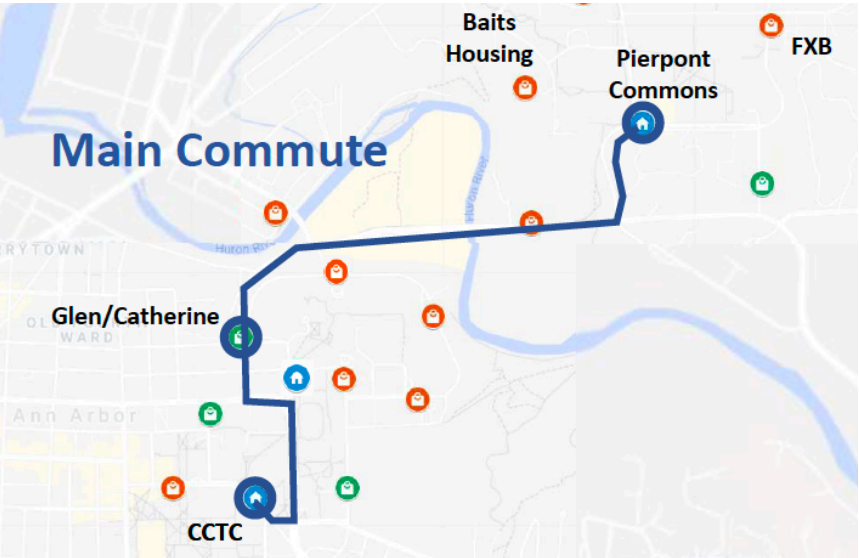


- *Replace all "UM Campus Routes" and "North-East Shuttle" with the six routes shown on the left (Main Commute, North 1, 2, 3, Central 1, 2). Keep Crisler Express, Med Express, Wall-street.*
- *Reduced # of bus stops to 50 (both directions; 25 in one direction.)*
- *We use min{# bus, # driver} available for each shift, and consider 5% buffer for driver shortage/mechanical failure.*
- *Total # buses in Main Commute: 20; North: 7--12, Central: 11, Medical: 14--9*

Key results: We compare the total # of rides that can be provided by our solution at 50% capacity with the one of original schedule & routes at 100% capacity and show that they are the same. If only half of the classes in person, then it is possible for the recommended schedule and routes to satisfy all ride demand even we can only use 25% capacity (theoretically speaking, which will be validated through simulation).

Match to Peak-time Ride Capacity

- Recommendation: Main Commute extracts the common part of Bursley-Baits, Northwood, Northwood Express, Commuter South/Commuter North, Diag-to-Diag Express by connecting main hubs.



Statistics	Values
Stops	3
Single-trip distance	2.4 miles
Single-trip time	11 mins
# buses	20 * 40’
Schedule	6:30am – 3am

	Current (100% capacity)		Hub-and-Spoke (50% capacity**)		
Time	Frequency	Capacity/h	Frequency	Capacity/h	# buses
6:30am - 8:30pm	Every 2 mins*	2100	Every 1.1 mins	1909	20
8:30pm - 3am	[2.72, 8.57] mins	[490, 1544]	Every 1.69 mins	1243	13

* Covered by five routes: Bursley-Baits, Northwood, Northwood Express, Commuter South/Commuter North, Diag-to-Diag Express.
** Using 50% capacity, one 40’ bus can accommodate 70*50%=35 passengers.

Simulation Design

We use ProModel® Better Decisions—Faster for simulation studies.

Compare bus schedules: Existing vs. Recommended, given our estimated ride patterns.

Input data

- Stops and schedules of different routes
- Hourly ride patterns and rates
  - ❑ Obtained using historical data, housing, parking, recreation, course enrolment data, etc.
  - ❑ Rides (including transfer plan) between "popular" stops
    - ➢ E.g., from Pierpont Commons to CCTC during 10-11 am for classes.
  - ❑ Randomly generated getting-on/-off passengers (0-3) at less popular stops.
- Travel time in between stops (from Google Map) and loading/unloading time at each stop.

Expected output statistics:

- Number of served rides
- Real time busload track & bus utilization rate
- Number of passengers waiting at each stop
- Waiting and traveling time of passengers

Sensitivity analysis:

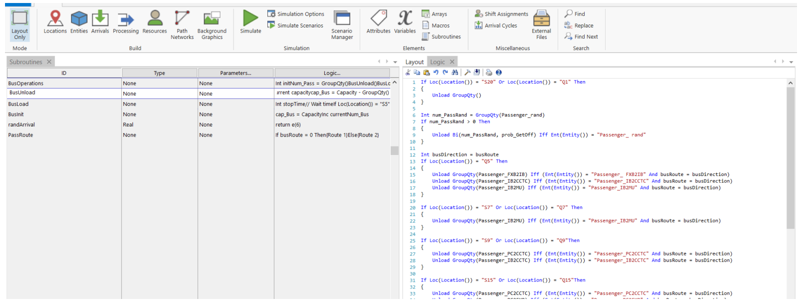
- E.g., varying bus capacity from 100% to 50% and then 25%; varying bus availability/frequency

Stress test of vulnerable events:

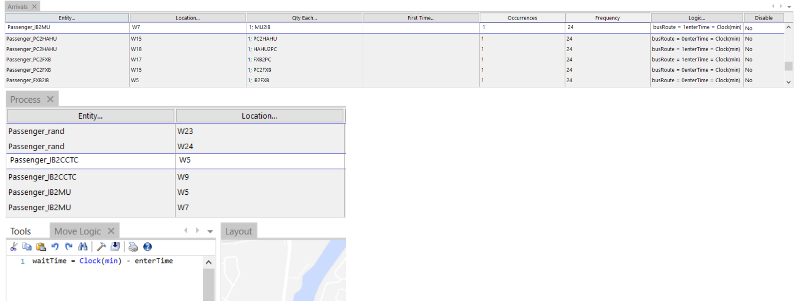
- E.g., lack of drivers, mechanical issues, peak hour demand

Simulation Result Output

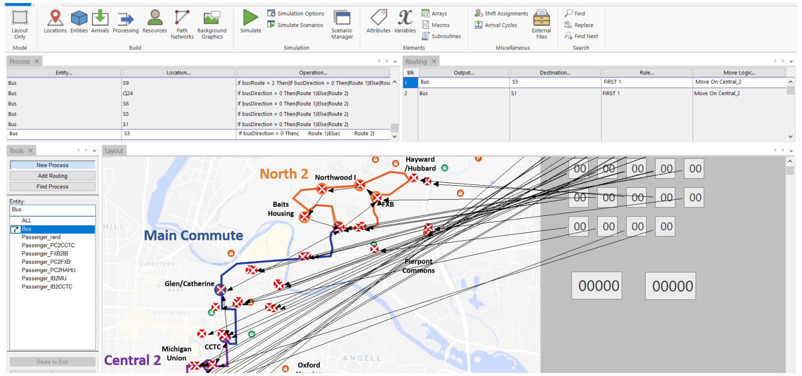
- Real time busload track & Bus utilization rate



- Passenger waiting, riding and walking analysis



- Number of passengers waiting at each stop



- Sensitivity analysis & Stress test

Scenario Manager

#	Parameters	Baseline	Scenario1	Scenario2	Scenario3	Scenario4
	Simulate Scenario?	☑	☑	☑	☑	☑
	Last Simulation Run					
*	Capacity	100	50	25	50	50
*	Max_Bus	50	50	50	50	50
*	Period_Bus_North	2.75	2.75	2.75	2.75	5
*	Period_Bus_Main	1.1	1.1	1.1	1.1	2.5
*	Period_Bus_Central	5	5	5	5	4
*	Prob_sudden_shortage	0	0	0	0.05	0.1

Simulation Platform Demonstration

Recommended route and schedule of North 2, **Main Commute**, and **Central 2**.

- cover similar stops to that of **CN** & **CS**.

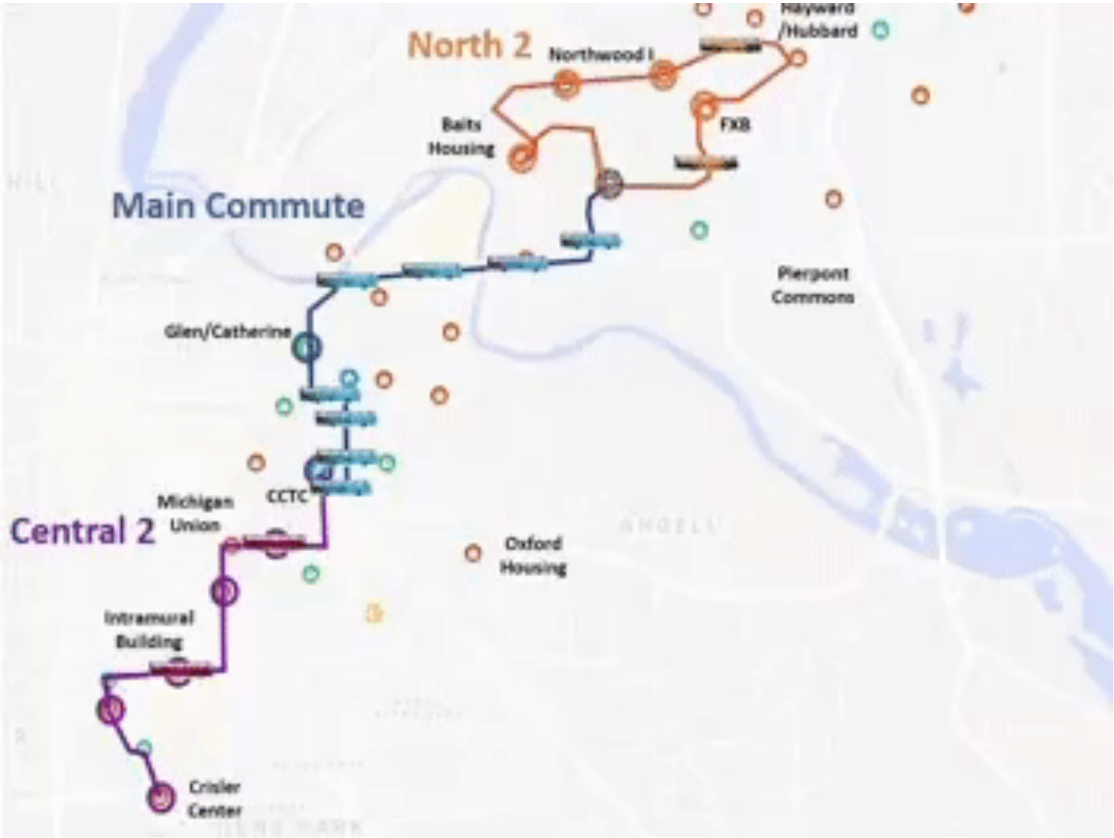
Operation Hour: 8-10 am

Single-trip Distance:
- North 2: 2.7 mile
- Main: 2.4 mile
- Central 2: 1.9 mile

Single-trip Time:
- North 2: 11 min
- Main: 11 min
- Central 2: 15 min

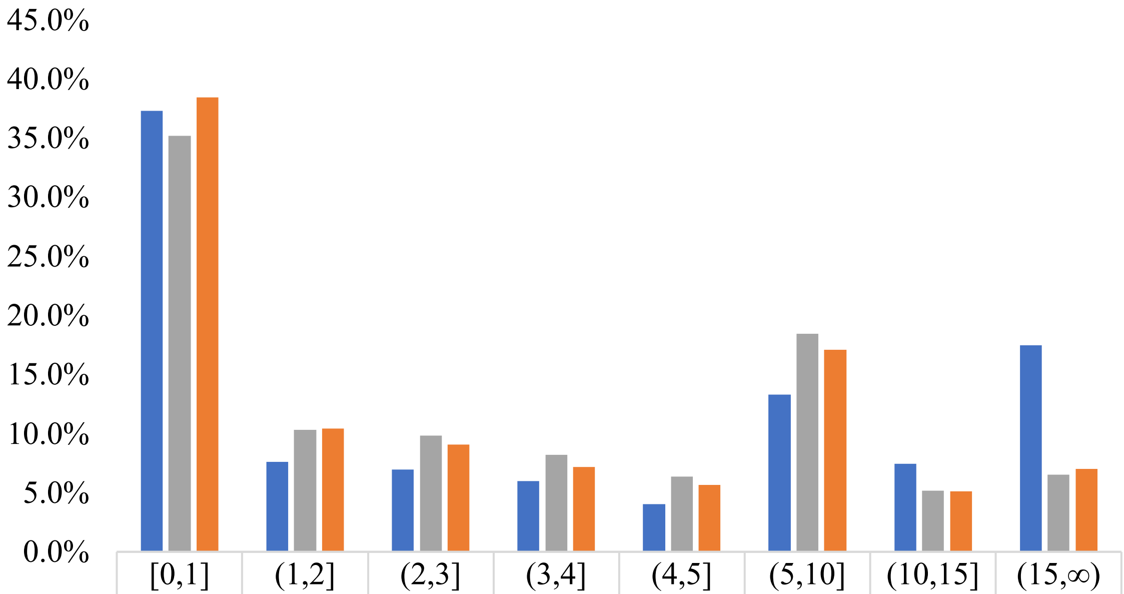
Stops:
- North 2: 5
- Main: 3
- Central 2: 6

Frequency:
- North 2: 1 every 2.75 min
- Main: 1 every 1.1 min
- Central 2: 5 every 5 min



Passenger Wait and Transit Times

- More than 35% passengers wait less than 1 minute.
- Reduction of bus capacity has no significant impact over individual passengers' wait time.



	[0,1]	(1,2]	(2,3]	(3,4]	(4,5]	(5,10]	(10,15]	(15,∞)
C=40, D=1500	37.3%	7.6%	7.0%	6.0%	4.0%	13.3%	7.5%	17.5%
C=20, D=1500	35.2%	10.3%	9.8%	8.2%	6.4%	18.4%	5.2%	6.5%
C=40, D=2625	38.4%	10.4%	9.1%	7.2%	5.7%	17.1%	5.1%	7.0%

Wait time range (unit: min)

- 70% passengers only take a single bus; 30% passengers make at least one transit.
- On average, passengers need to take 1.3 buses to complete their trips.

Results of Random Bus Breakdown

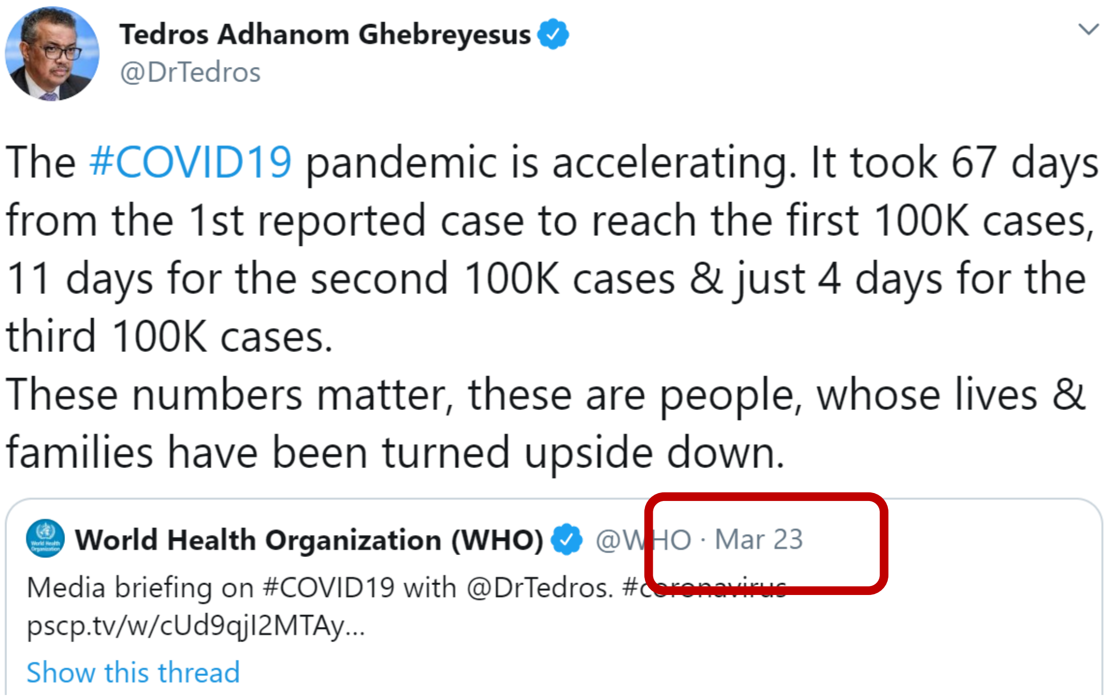
Result per passenger (in minute)	No bus removed	Central 1 Bus -1	Central 2 Bus - 1	Main Bus -1	North 1 Bus -1	North 2 Bus -1	North 3 Bus -1
Avg. time in system (riding + waiting)	18.51	18.70	19.33	18.57	18.81	18.59	17.59
Avg. time on wait	5.32	5.54	6.29	5.45	5.64	5.43	4.86
% wait > 5 min	29.23%	29.81%	32.67%	29.77%	30.68%	29.56%	31.85%

- All time is per passenger, in minute.
- % wait > 5 min is the percentage of passengers who wait more than 5 minutes among total number of passengers
- Removal of one bus from Central 2 has the greatest impact overall. However, the maximum change is less than 1 minute longer waiting time per passenger, and the system is quite robust with respect to one bus breakdown in any route.

Outline

- ❑Introduction
- ❑COVID-19 and Mobility
- ❑Business Reopening / Lockdown
- ❑Redesign Public Transit Systems
- ❑**Conclusion**

From Data to Actions, to Solutions



Tedros Adhanom Ghebreyesus
@DrTedros

The #COVID19 pandemic is accelerating. It took 67 days from the 1st reported case to reach the first 100K cases, 11 days for the second 100K cases & just 4 days for the third 100K cases.
These numbers matter, these are people, whose lives & families have been turned upside down.

World Health Organization (WHO) @WHO · Mar 23
Media briefing on #COVID19 with @DrTedros. #coronavirus
pscp.tv/w/cUd9qjI2MTAy...
Show this thread

As of April 26, there are almost 1 million infected cases and 55,443 deaths from the U.S.

As of Sept 21, there are close to 7 million infected cases and 202,000+ deaths from the U.S.

- **Enhancing community-based control of self-quarantine; tracking the paths of disease spread; warning people with potential high risk of infection.**
- **Increasing COVID-19 testing availability and making information transparent to the public. (Testing! Testing! Testing!)**
- **Avoiding medical supply shortage and avoiding exceeding healthcare capacity.**
- **Triaging patients to avoid cross-infection in hospitals. Gathering all patients with mild symptoms to a central quarantine place for treatment.**
- **Limiting travel and other non-essential activities, canceling social gathering, implementing `Shelter-in-Place’ and `Stay-at-Home’ policies.**

THANK YOU!

Questions?