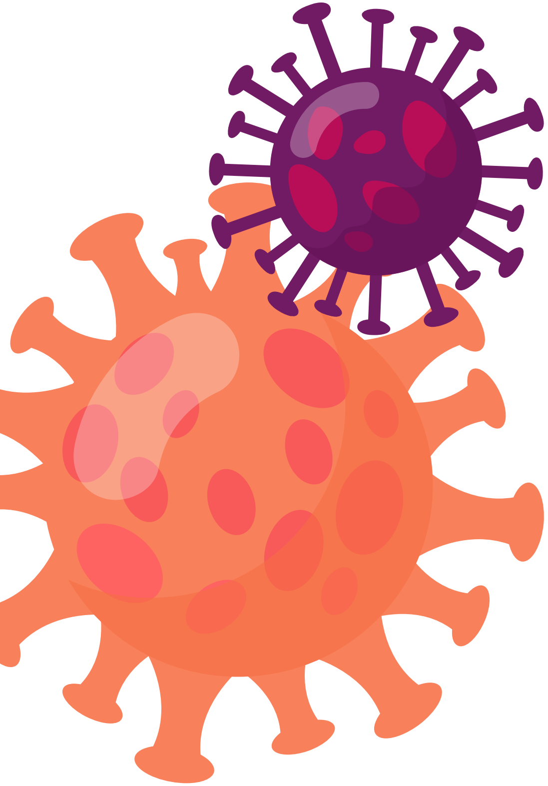

# Vaccine Distribution Optimization for Montréal’s COVID-19 Response

**Decision Analytics MGSC 662 : Group 3855 - 1**

By Audrey Delisle, Samia Belmadani, Tiffany Lagarde, Dhevin DeSilva, Julien Palummo

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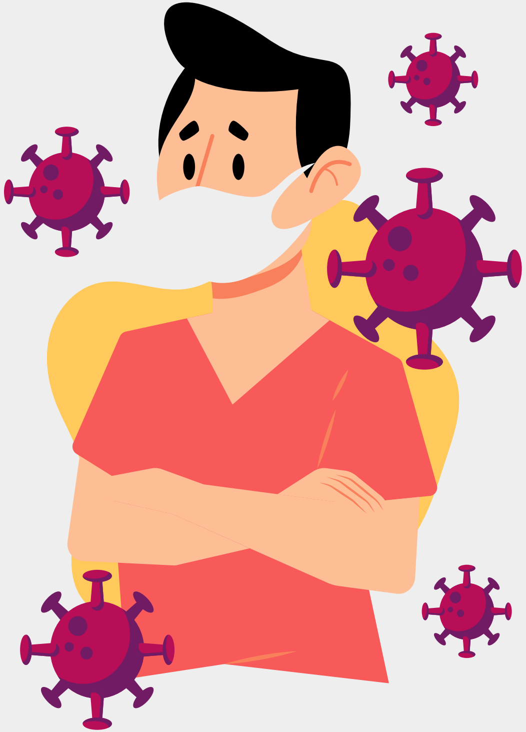
# SECTION 1 : INTRODUCTION



# SELECTED TOPIC : COVID - 19


**A new COVID-19 variant is spreading in Quebec...**
Aug. 31, 2023 11:30 a.m. EDT
By Caroline Van Vlaardingen & Keila DePape - CTV News Montreal

**Early signs suggest fall COVID-19 wave starting in Canada...**
Aug 18, 2023 4:00 AM
By Lauren Pelley - CBC News

**Canada 'likely at the start' of new COVID-19 wave. How big will it get?**
August 28, 2023 6:19 am
By Aaron D'Andrea - Global News

# MAIN PROBLEM DESCRIPTION

**Category :** Unbalanced Inventory Problem

**Problem:** We have an unbalanced weekly vaccine demand and supply. For 1 week, we want to distribute the supply we do have as optimally as possible all the while incurring the least transportation costs and unmet demand penalties. We are looking at t=0-4 (Oct-Nov), knowing demand/urgency changes week over week.

Distribution Facilities (Suppliers) = i

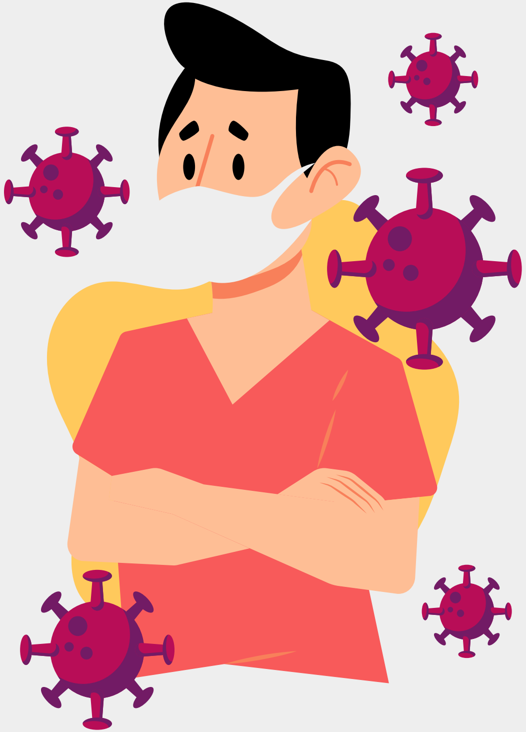
33,815 over t,i

≠

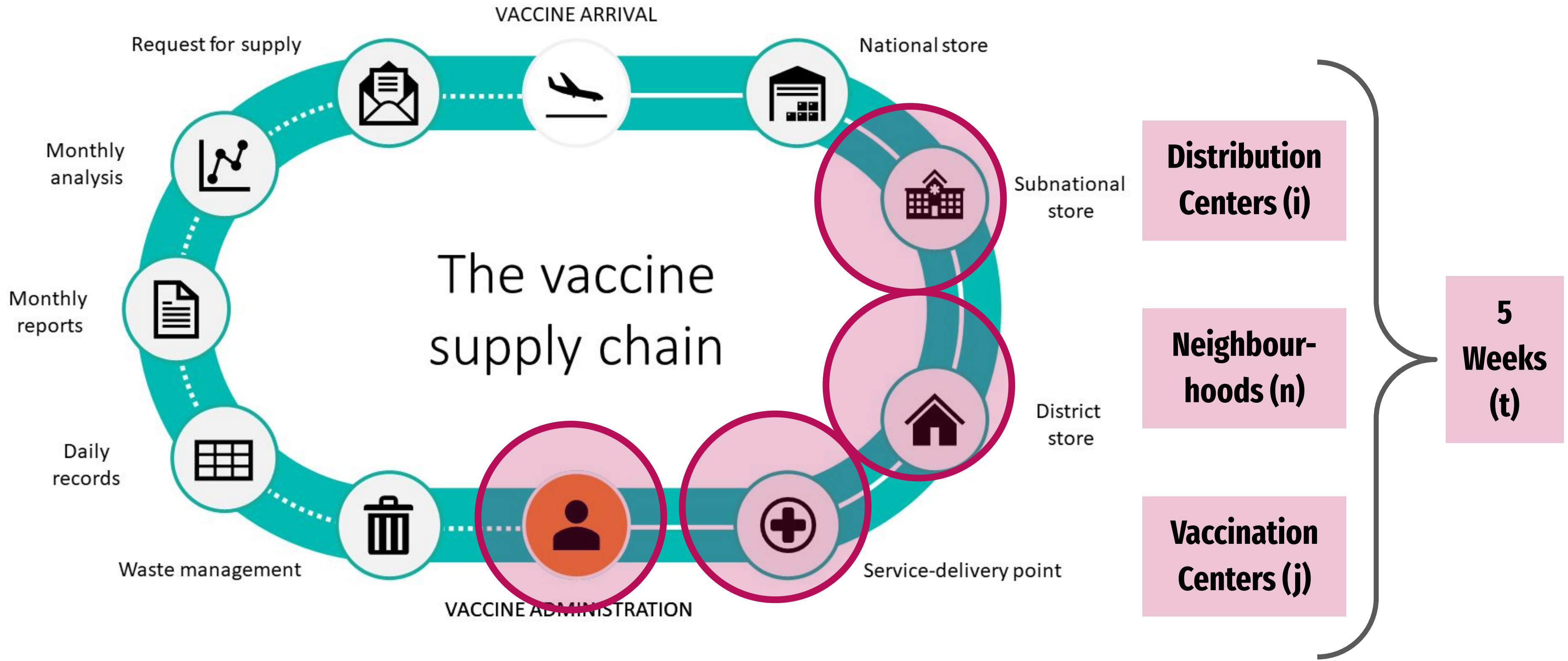
Vaccination Centers (Buyer) = j

35,182 over t,n

# SECTION 2 : PROBLEM DESCRIPTION



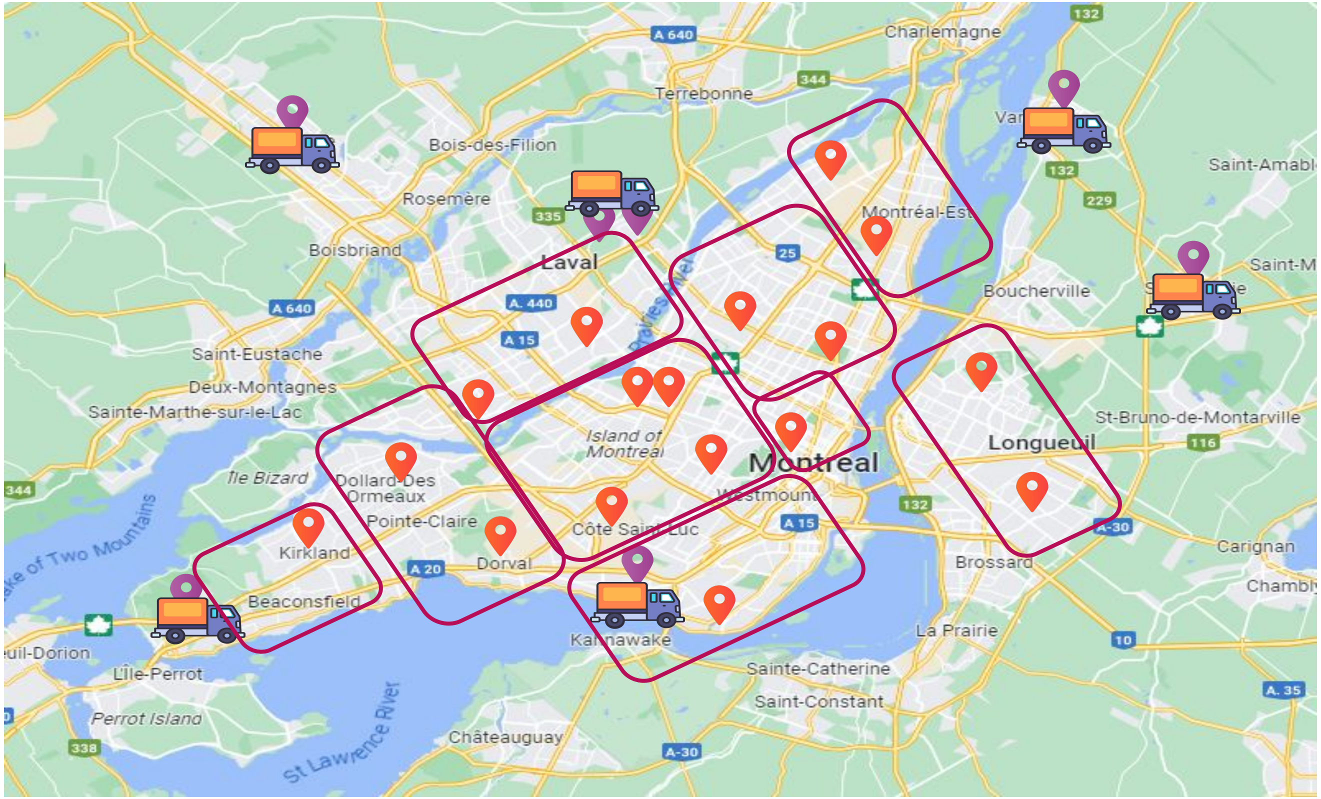
# PROBLEM CONTEXT





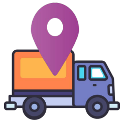

Graph Source: https://www.who.int/teams/immunization-vaccines-and-biologicals/essential-programme-on-immunization/supply-chain

# PROBLEM VISUALIZATION




* Not exact, only for visualization purposes

# PARAMETER DESCRIPTIONS

| Icon | Description | Variable | Amount |
|---|---|---|---|
|  | Distribution Facilities | i | 6 (vaccine suppliers) |
| | Neighbourhoods | n | 9 |
|  | Vaccination Centers | j | 17 |
| | Week | t | 5 in total: October 15 - November 18 (t=0-4) |

# GOALS OF OPTIMIZATION

1

MINIMIZE DAILY TRANSPORTATION COSTS OF VACCINES FROM SUPPLIER i TO CENTER j

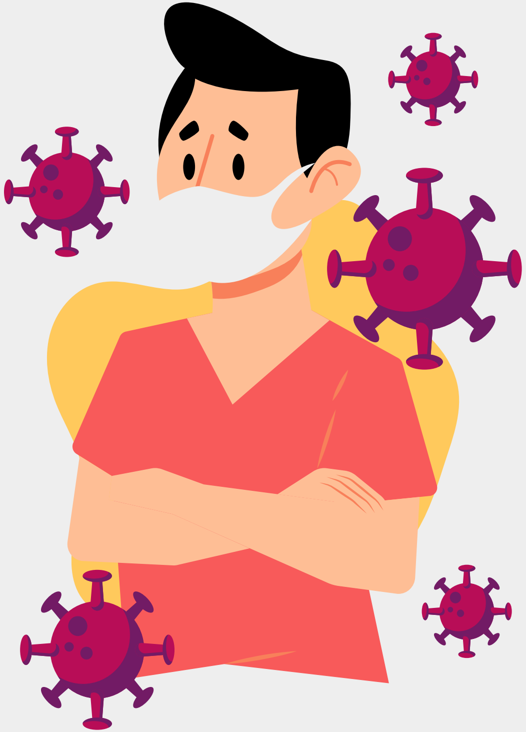

2

MINIMIZE COSTS RELATED TO UNMET DEMAND IN NEIGHBOURHOOD n

3

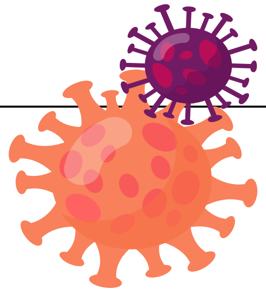
MINIMIZE URGENCY PENALTY RELATED TO UNMET DEMAND IN NEIGHBOURHOOD n

# SECTION 3 : DATA COLLECTION

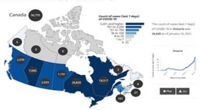


# DATA SOURCES - Supply

| Source | Description |
|---|---|
| Statistics Canada | • Provides population proportion of Quebec vs Canada and Montreal versus Quebec to help us with the calculation of supplies<br>• Initial agreement number of vaccines that suppliers will supply to Canada for a year |
| Github | • Weekly vaccines supply to Canada |
| Statista | • Vaccine purchase costs from various suppliers |



# DATA SOURCES - Demand

| Source | Description |
|---|---|
| Statistics Canada | • Provides data on target immunization rates in Canada<br>• Offers historical data on vaccination rates<br>• Provides information on high-risk age boundaries |
| <br>Health Infobase Canada | • Provides the number of weekly COVID-19 deaths<br>• Provides the number of weekly COVID-19 cases |

# DATA COLLECTED

01

**Supplier data :** Supplier Location, Supply quantity of vaccine i, vaccine i price

02

**Region data :** Vaccination Center location, neighbourhood to center association, demand quantity from neighbourhood n

03

**Transportation Costs :** Matrix of cost of transportation from supplier i to center j

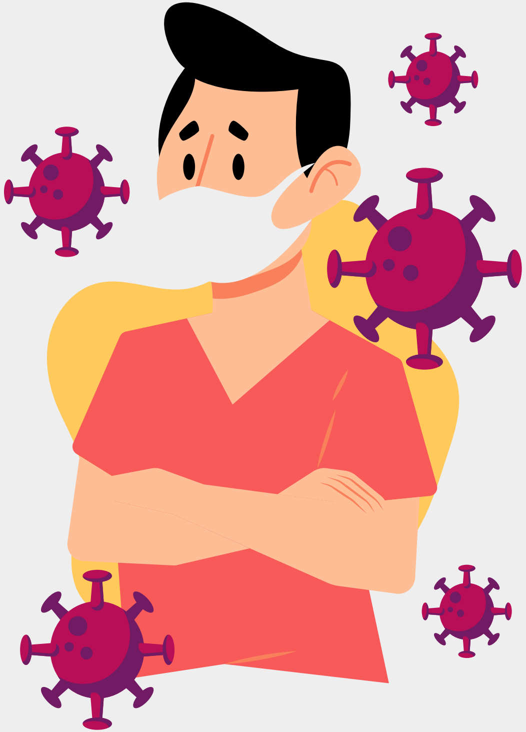
04

**Unmet demand costs :** Cost of 1 person catching serious case of Covid due to unmet demand

05

**Urgency factors :** Amount of cases and deaths per neighbourhood at time t

# SECTION 4 : MATHEMATICAL FORMULATION



# PARAMETERS

| | |
|---|---|
| $p_i$ | Price of one vaccine from supplier i |
| $t_{i,j}$ | Transportation cost from supplier i to center j |
| $c_n$ | Number of COVID-19 cases in neighbourhood n |
| $d_n$ | Number of COVID-19 deaths in neighbourhood n |
| $\alpha$ | Weighting factor representing the importance of Covid-19 cases (0.05) |
| $\beta$ | Weighting factor representing the importance of Covid-19 deaths (0.1) |
| h | Medical costs associated with 1 person catching Covid (1,000) |
| $D_{n,t}$ | Vaccine demand (based on population) in neighbourhood n at time t |



* Average cost for COVID-19 ICU patients estimated at more than $50,000 (https://www.cbc.ca/news/health/cihi-covid19-canada-hospital-cost-1.6168531)

# PARAMETER RATIONALE

| h | Alpha | Beta |
|---|---|---|
| 1,000 | 0.05 | 0.1 |

-CBC estimates the average cost for COVID-19 ICU patients, to **$50,000.**
- Likelihood of hospitalization, approximately **20%** for individuals who contract COVID-19.
- Assuming that around **10%** of unvaccinated individuals may catch COVID-19
- 'h' penalty to be **$1,000**, considering these probabilities (50,000*0.2*0.1).

- Deaths were considered more critical than cases, hence a **higher weight to 'β'** (0.1) and a **lower weight to 'α'** (0.05).
  - Does **not exceed** the general penalty ('h').
- Estimated the urgency penalty to be around **20-40% of the general penalty**, equivalent to approximately $200-$400.
- Through trial and error, we determined that 'α' and 'β' should be **approximately 0.1**'
- Urgency = approximately **$355**, completing our parameter choices.



* Average cost for COVID-19 ICU patients estimated at more than $50,000 (https://www.cbc.ca/news/health/cihi-covid19-canada-hospital-cost-1.6168531)

# DECISION VARIABLES

1

$X_{ijt}$ : Number of vaccines transported from supplier i to vaccination center j for week t

# OBJECTIVE FUNCTION

$$Z=\sum_{i,j,t}(p_i+t_{i,j})\times x_{ijt}+\sum_{n,t}(h+u_{nt})\times(D_{nt}-\sum_{i\in I(n),j}x_{ijt})$$

Cost of Procurement and Transportation

General Costs incurred for Unmet Demand ($)

Penalty for Unmet Demand in high intensity areas

Unmet demand

*$i\in I(n)$ = vaccination centers i included in neighbourhood n

The overall objective is to minimize the combined cost of procuring and transporting vaccines while considering general penalties for unmet demand (monetary healthcare fees) and a penalty factor associated to incurring unmet demand in a high urgency neighbourhood at time t.

# OBJECTIVE FUNCTION : TRANSPORT & PROCUREMENT COST

$$Z=\sum_{i,j,t}(p_i+t_{i,j})\times x_{ijt}$$

This part represents the total cost of procuring and transporting vaccines from suppliers to vaccination centers.

$p_i$ : Price of one vaccine from supplier i.
$t_{i,j}$ : Transportation cost from supplier i to vaccination center j.
$x_{ijt}$ : Number of vaccines transported from supplier i to vaccination center j for week t.

# OBJECTIVE FUNCTION : UNMET DEMAND PENALTY (GENERAL)

$$\sum_{n,t}(h*\text{unmet demand})$$

This part represents the general monetary penalty associated with unmet demand in each region.

h: Monetary cost for 1 person catching serious case of Covid (healthcare fees).

# OBJECTIVE FUNCTION : UNMET DEMAND PENALTY (URGENCY)

$$\sum_{n,t}(u_{n,t} * \text{unmet demand})$$

This part represents the penalty associated with unmet demand in highly critical areas (urgency), taking into account COVID-19 cases and death rates. Hence, the penalty is higher when fewer vaccines are transported to critical areas.

$$u_{nt} = \alpha \cdot \text{Cases}_{nt} + \beta \cdot \text{Deaths}_{nt}$$

$\alpha$, $\beta$ : Weighting factors
$c_{n,t}$ : Number of COVID-19 cases in neighbourhood n at time t.
$d_{n,t}$ : Number of COVID-19 deaths in neighbourhood n at time t.

# CONSTRAINTS

### 1. Supply Constraints:

Ensure that the total vaccines supplied by each supplier to each vaccination center at each time period do not exceed the available supply.

$$\Sigma_{j,t}\ X_{i,j,t} \leq \text{Supply}_{i,t}$$

### 2. Demand Constraints:

Ensure that the total vaccines distributed to each neighborhood's vaccination centers at each time period do not exceed the total demand for vaccines in that neighborhood.

$$\Sigma_{i,j}\ X_{i,j,t} \leq \text{Demand}_{n,t}$$

### 3. Proportion of Demand Met:

Ensure that at least 10% of the demand in each neighborhood is met by the vaccines distributed at each time period.

$$\Sigma_{i,j} X_{i,j,t} \geq 0.1 * \text{Demand}_{n,t}$$

### 4. Non-negativity Constraints:

Ensure that the number of vaccines transported from each supplier to each vaccination center at each time period is non-negative.

$$X_{i,j,t} \geq 0$$

# CONSTRAINTS

### 5. Supply < Than Demand Indicator:

Introduce binary variables to indicate if the total supply is less than total demand at each time period. Ensure that if this indicator is 1, the total supply is indeed less than demand.

$$supply\_less\_than\_demand_t$$

### 6. Use All Supply When Less:

Ensure that if the supply is less than demand at a time period, all available supply is used, and no vaccines remain unused.

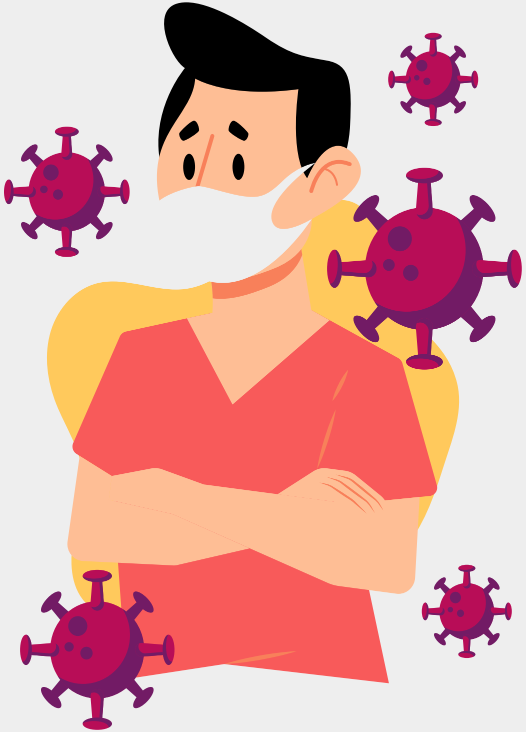
$$\Sigma_{i,j} X_{i,j,t} = Total\_supply_{t,\ when\ supply\_less\_than\_demand=1}$$

### 7. Equal Distribution Constraints:

Ensure that vaccines are equally distributed among vaccination centers within each neighborhood at each time period.

$$\Sigma_{i,t} X_{i,j,t} = total\_vaccines\_for\_neighbourhood / num\_centers\_in\_neighbourhood$$

# SECTION 5 : RESULTS



# GUROBIPY SOLUTION

| | | Kirkland | Lachine | Berri-UQAM | Verdun | Parc-Extension | Décarie | Saint-Laurent | Montréal-Nord | Chauveau | CLSC Est | Saint-Michel | Montérégie-Centre | Montérégie-Ouest | Laval | Laurentides | Universitaire De Sante | Lanaudière |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t=0 | Moderna | | 72 | 207 | | 181 | 175 | 61 | | | | | | 182 | | | | |
| | Pfizer-BioNTech | | | | | | 6 | | | | | | | | 665 | 366 | 181 | |
| | Johnson & Johnson (Janssen) | | | | | | | | | | | | | 907 | | | | |
| | AstraZeneca | 275 | 203 | | | | | | | | | | | | | | | |
| | Novavax | | | | 207 | | | | | | | 262 | 750 | | | 596 | | |
| | Sanofi and GlaxoSmithKline | | | | | | | | 61 | 262 | 262 | | 339 | | | | | 795 |
| t=1 | Moderna | | 274 | 58 | 58 | 180 | | 61 | | | | | | 112 | | | | |
| | Pfizer-BioNTech | 274 | | | | 1 | 181 | | 61 | | | | | | 67 | 96 | 181 | |
| | Johnson & Johnson (Janssen) | | | | | | | | | | | | | 641 | | | | |
| | AstraZeneca | | | | | | | | | | | | | 338 | | | | |
| | Novavax | | | | | | | | | | | 203 | 1080 | | | | | |
| | Sanofi and GlaxoSmithKline | | | | | | | | | 203 | 203 | | 11 | | | | | 798 |
| t=2 | Moderna | | 274 | 47 | | 181 | | 44 | | | | | | 180 | | | | |
| | Pfizer-BioNTech | 274 | | | | | 181 | | 43 | | | | | | 67 | 96 | 181 | |
| | Johnson & Johnson (Janssen) | | | | 47 | | | | | | | | | 580 | | | | |
| | AstraZeneca | | | | | | | | | | | | | 330 | | | | |
| | Novavax | | | | | | | | | | | 186 | 1069 | | | | | |
| | Sanofi and GlaxoSmithKline | | | | | | | | 1 | 186 | 186 | | 21 | | | | | 795 |
| t=3 | Moderna | | 50 | 120 | | 184 | | 62 | | | | | | 128 | | | | |
| | Pfizer-BioNTech | | | | | | 184 | | | | | | | | 668 | 258 | 184 | |
| | Johnson & Johnson (Janssen) | | | | | | | | | | | | | 964 | | | | |
| | AstraZeneca | 279 | 229 | | | | | | | | | | | | | | | |
| | Novavax | | | | 210 | | | | | | | 265 | 750 | | | 704 | | |
| | Sanofi and GlaxoSmithKline | | | 90 | | | | | 62 | 265 | 265 | | 342 | | | | | 803 |
| t=4 | Moderna | | | | | | | | | | | | | | | | | |
| | Pfizer-BioNTech | | | | | 181 | 181 | | | | | | | | 666 | 305 | 181 | |
| | Johnson & Johnson (Janssen) | | | 18 | | | | 15 | | | | | | 1095 | | | | |
| | AstraZeneca | 274 | 274 | | | | | 46 | | | | | | | | | | |
| | Novavax | | | | 207 | | | | | | | 261 | 527 | | | 657 | | |
| | Sanofi and GlaxoSmithKline | | | 189 | | | | | 61 | 261 | 261 | | 568 | | | | | 798 |

TOTAL Cost: $13,996,643.87 CAD

Direct Costs: $8,541,303.01 CAD

TOTAL Supply: 31,157 vaccines

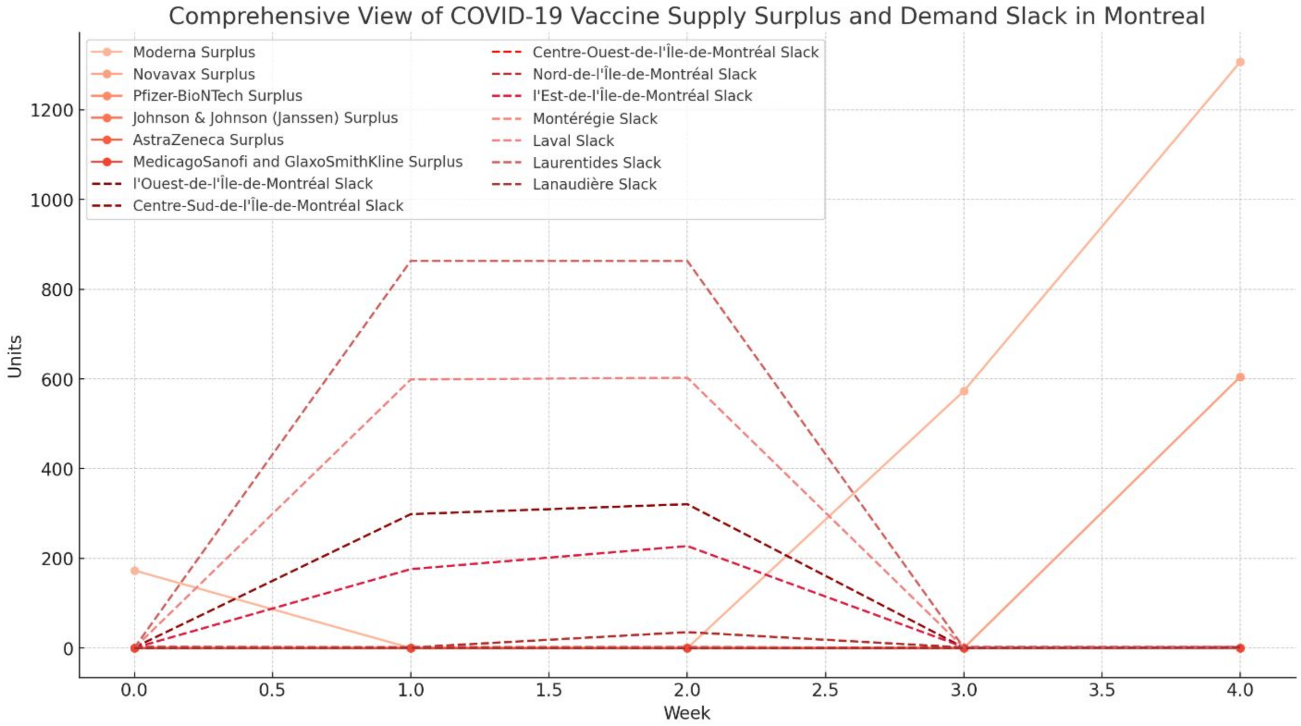
# TOTAL NUMBER OF VACCINES PER SUPPLIER

| | |
|---|---|
| Moderna | 2,891 vaccines |
| Pfizer BioNtech | 5,729 vaccines |
| AstraZeneca | 2,228 vaccines |
| Novavax | 7,934 vaccines |
| Sanofi GlaxoSmithKline | 8,088 vaccines |
| Johnson and Johnson | 4,267 vaccines |

## Total number of vaccines per day

| | |
|---|---|
| t=1 | 7,015 |
| t=2 | 5,081 |
| t=3 | 4,969 |
| t=4 | 7,066 |
| t=5 | 7,026 |

# SENSITIVITY ANALYSIS




## Key Findings:

- The analysis revealed geographical disparities in vaccine demand fulfillment.
- Instances where vaccine supply exceeded demand, highlighting the need for a dynamic approach to distribution.
- The model's strict adherence to non-negativity constraints ensure that the distribution plan remained within realistic and feasible parameters.

# IS RESPONSE LOGICAL?

**Gov Can Covid-19 Expenditure 2021-22**

**22.1 billion**
(not including wage subsidies)

**Initial solution**

**13.99 million**
for 5 weeks in MTL

* 10.4 (52/5)

**Yearly outlook**

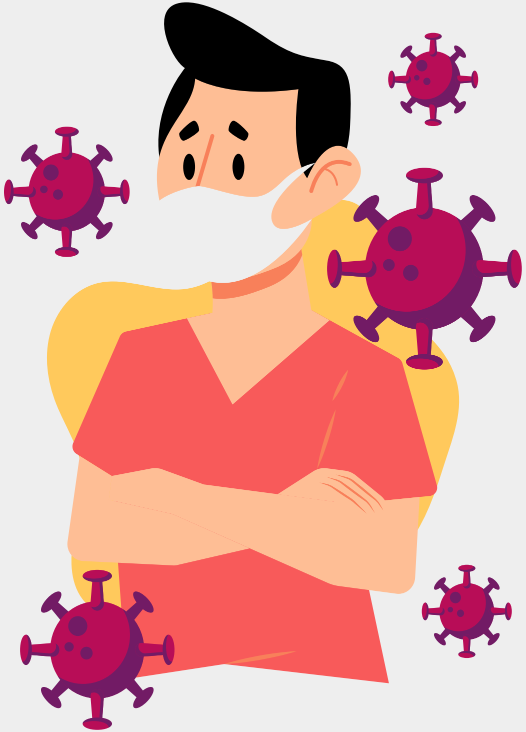
**145 million**
yearly in MTL

* 20 (Mtl is around 5% of Cad pop)

**Country outlook**

**2.9 billion**
million yearly in Canada

# SECTION 6 : PROBLEM EXTENSIONS



# EXTENSION 1 : HISTORICAL VACCINE ALLOCATION IN URGENCY

- For urgency factor, we originally wanted to include not only cases and deaths, but also vaccines distributed at week t-1 (cumulative).

- We were not able to find a working code but with more time and knowledge, this would be an interesting extension

```
In [21]:
#urgency_penalty = gp.quicksum(
#    (alpha * cases[n][t] + beta * deaths[n][t]
#    for n in neighbourhood_vacc_centers
#    for t in time_periods
#))

# Urgency penalty from problem extension
urgency_penalty = gp.quicksum(
    (alpha * cases[n][t] + beta * deaths[n][t] - gp.quicksum(X[j, i, t-1] for i in neighbourhood_vacc_centers[n] for j in sup
    * (demand[n][t] - gp.quicksum(X[j, i, t] for i in neighbourhood_vacc_centers[n] for j in suppliers))
    for n in neighbourhood_vacc_centers
    for t in time_periods if t > 1
)

print(urgency_penalty)
# General Unmet demand
penalty_unmet_demand = gp.quicksum(
    (h+urgency_penalty) * (demand[n][t] - gp.quicksum(X[j, i, t] for i in neighbourhood_vacc_centers[n] for j in suppliers))
    for n in neighbourhood_vacc_centers
    for t in time_periods
)
```

```
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```

$$u_{nt} = \alpha \cdot \mathrm{Cases}_{nt} + \beta \cdot \mathrm{Deaths}_{nt} - \gamma \cdot \sum_{i \in I(n),j} x_{ij,t-1} \quad \text{for } t>1$$

# EXTENSION 2 : ADDING GOVERNMENT BUDGET CONSTRAINT

## Financial Limitation Integration

- Incorporating a budget constraint mirrors real-world fiscal constraints on vaccine-related expenses.

## Balanced Approach to Distribution

- Ensures a delicate balance between meeting vaccine demand and operating within allocated financial resources.

## Optimization Impact

- Results in a decrease in transported vaccines, emphasizing cost efficiency while maintaining a careful balance between demand fulfillment and cost-effectiveness.

$$\sum_{i,j,t}(p_i+t_{i,j})\times x_{ijt} \leq \boldsymbol{B}$$

# EXTENSION 3 : EXTENDING SCOPE TO WASTE MANAGEMENT

## Wastage Penalty Addition

- Incorporation of a wastage penalty within the model introduces a cost factor for proper disposal of unused or expired vaccines.

## Minimization Incentive

- This penalty mechanism incentivizes minimizing wastage by imposing financial repercussions linked to the quantity of wasted vaccines, aligning with directives to keep national vaccine wastage below 5% set by the Public Health Agency of Canada (PHAC).

$$\sum_{i,j,t} w \times W_{i,j,t}$$

*$w$ : The wastage penalty cost*
*$W_{i,j,t}$: The quantity of wasted vaccines from supplier i at vaccine center j for week t*

# EXTENSION 4 : OTHER CONSTRAINTS

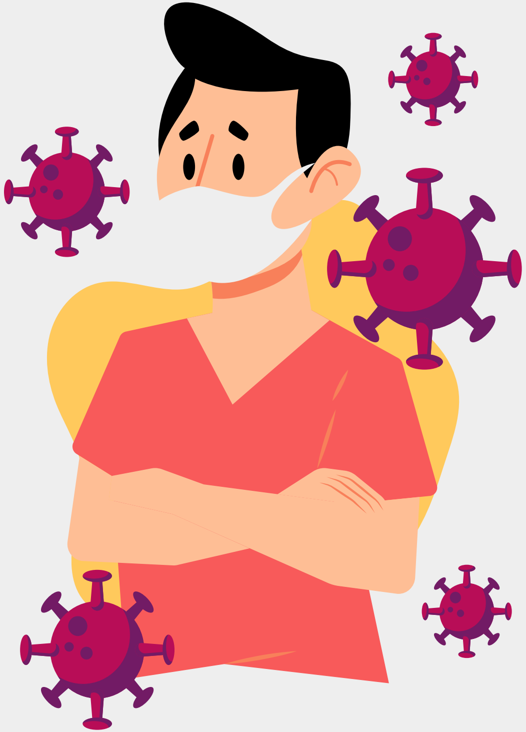
## Age Constraint

- The age-related limitations in certain vaccines (e.g., AstraZeneca, Johnson & Johnson) enables the optimization model to tailor distribution strategies, ensuring compliance with regulatory advisories and addressing safety concerns specific to particular age groups.

## Temperature  Constraint

- Temperature constraints, exemplified by Pfizer and Moderna vaccines requiring storage at -70°C and -20°C respectively, impose critical logistical challenges necessitating meticulous planning and infrastructure readiness, significantly impacting their distribution logistics within the supply chain.

# SECTION 7 : RECOMMENDATIONS & CONCLUSION



# FINAL RECOMMENDATIONS

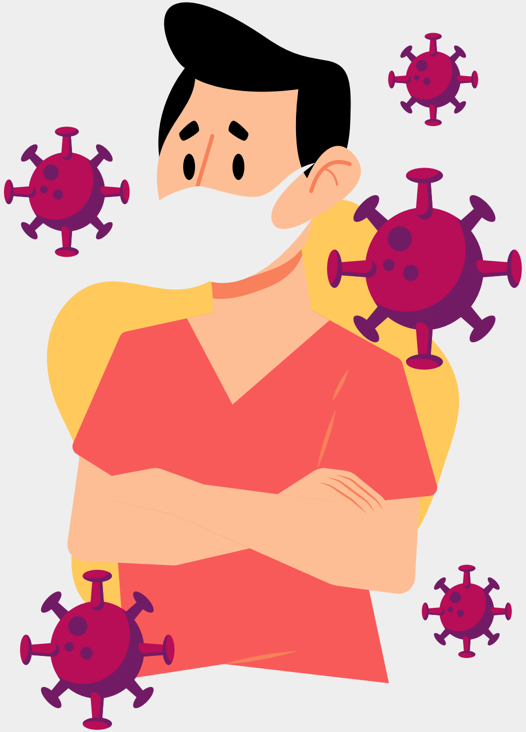
Strengthen the government's relationship with **Novavax as a primary vaccine supplier** for the future.

Prioritize resource allocation and boost infrastructure and staffing in **high-demand vaccination centers like Montérégie-Centre and Lanaudière,** while maintaining cost-effective distribution strategies.

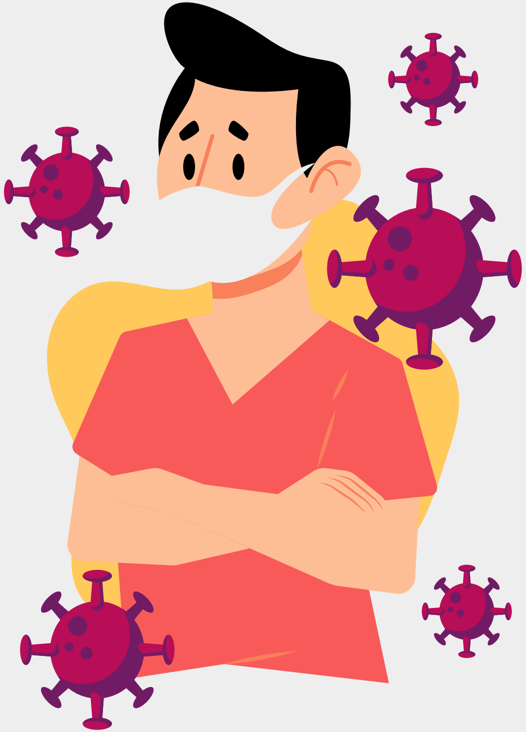
Reassess and potentially re-negotiate terms with **lower-contributing suppliers like AstraZeneca**.

# THANK YOU

IF YOU HAVE ANY QUESTIONS, FEEL FREE TO ASK!



# SECTION 8 : RESSOURCES



# RESSOURCES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