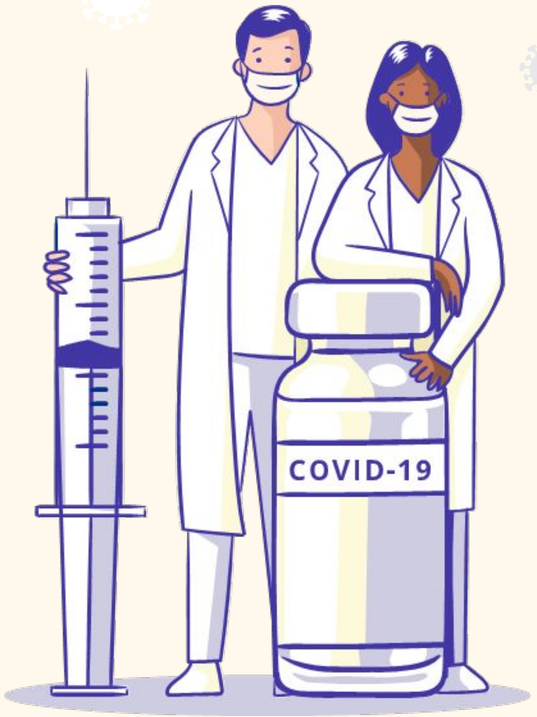
When a Pandemic Becomes a Supply Chain Challenge

- Over 6 million deaths and 600 million infections worldwide since December 2019
- Governments faced unprecedented demand for medical supplies under strict time constraints
- Traditional supply chains collapsed—cold storage, transportation, and equitable distribution became critical bottlenecks
- **The challenge**: How do you distribute life-saving vaccines fairly while minimizing human suffering?

A Humanitarian cold supply chain distribution model with equity Consideration

The case of COVID-19 vaccine distribution in the European Union



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Introduction

Why Cold Supply Chains Matter?

More Than Just Keeping Things Cool

- COVID-19 vaccines require ultra-cold storage: Pfizer at -70°C, Moderna at -25°C to -15°C
- Cold chain breakdown = wasted vaccines = lost lives
- **Technical challenges**: Specialized refrigerated trucks, temperature monitoring, limited storage capacity
- **Ethical challenges**: Who gets vaccines first? How do we ensure fair distribution across regions?

The Equity Dilemma

When Logistics Decisions Become Life-or-Death Choices

- Wealthy regions received vaccines faster than developing areas
- Example: EU, UK, and US received 513 million doses in 6 weeks (late 2021) while all of Africa received only 500 million doses in the entire year
- **Key question**: Should vaccine distribution prioritize efficiency (lowest cost) or equity (fairness)?
- Traditional supply chain models ignore the human cost of delays and inequitable distribution

02

Literature Review

What Previous Research Got Right

- **Cold chain optimization**: Models for temperature-controlled transportation and storage capacity
- **Vaccine supply networks**: Multi-echelon systems connecting manufacturers to end users
- **Humanitarian logistics**: Framework for disaster response and emergency distribution
- **Limitation**: Most studies focus on minimizing costs or maximizing efficiency, not human welfare

The Missing Pieces in Current Models

- **Gap 1**: Time-based **suffering costs** (what happens when people wait too long?)
- **Gap 2**: **Equity constraints** (how do we ensure fair distribution?)
- **Gap 3**: Real-world cold chain complexity in pandemic conditions
- **Gap 4**: Integration of **social costs** with traditional logistics costs

Introducing Deprivation Cost

Measuring Human Suffering in Supply Chain Terms

- **Deprivation cost**: Economic value assigned to human suffering when critical goods are delayed or unavailable
- **Why it matters**: A €1000 logistics savings might cause €10,000 worth of human suffering
- **Time-dependent**: Suffering increases non-linearly the longer people wait
- **Research innovation**: This study is among the first to integrate deprivation cost into cold supply chain optimization

Comparing Five Decision-Making Models

Model Type	Key Idea	Strength	Weakness
Social Cost	Logistics costs + deprivation costs	Realistic and fair	Complex
Variable Penalty	Penalizes late deliveries based on delay length	Can mimic suffering if well-designed	Still misses future suffering
Constant Penalty	Charges fixed penalty if threshold exceeded	Simple	Not realistic
Hard Constraints	Forces service within fixed time	Easy to understand	Often infeasible
Unmet Demand	Minimizes shortage quantities	Intuitive	Ignores time and urgency

The Social Cost Model: An Ideal Approach

Total Cost Calculation

Total Cost = Logistics Cost + Sum (Deprivation Cost at each node and time).

Nonlinear Deprivation

Deprivation cost is nonlinear and convex, meaning costs grow faster over time based on deprivation duration.

Inter-Temporal Externalities

This model tracks how current actions affect future suffering. Delivering aid now reduces future deprivation costs.

Estimating Deprivation Cost Functions:

1. Contingent Valuation (CV) Approach

- Based on stated preference techniques and hypothetical scenarios.
- Respondents express their willingness to pay (WTP) to access critical goods or services during deprivation.
- Econometric models (e.g., exponential or polynomial regression) are used to estimate the deprivation cost as a nonlinear, increasing, and convex function of deprivation time.
- Practical for rapid assessments and usable in mathematical models of humanitarian logistics.

2. Discrete Choice Modeling (DCM) Approach

- Grounded in random utility theory and choice behavior analysis.
- Individuals choose between alternatives (e.g., buying vs. waiting), revealing preferences under scarcity.
- Estimated using Mixed Logit models, capturing both systematic (e.g., age, gender) and random preference heterogeneity.
- Produces socially disaggregated, flexible DCFs suitable for equity-aware resource allocation.

03

Problem Statement

Problem Statement:

- A mathematical model is developed to minimize total cost, including logistics and social costs.
- Focuses on rapid and equitable vaccine distribution during pandemics like COVID-19.
- Equity ≠ equal quantity, but equal proportion of vaccinated population across affected regions (ARs).
- Deprivation cost is time-dependent, tracking delays between order and delivery.
- Distribution is split across periods due to real-world constraints:
    - Limited production & storage
    - Machine/vehicle limits
    - Cold chain requirements for perishable vaccines
- Deterioration cost excluded due to real-world high turnover and urgent use.

Sets:

I: index for suppliers ($i = 1, 2, \ldots, I$)

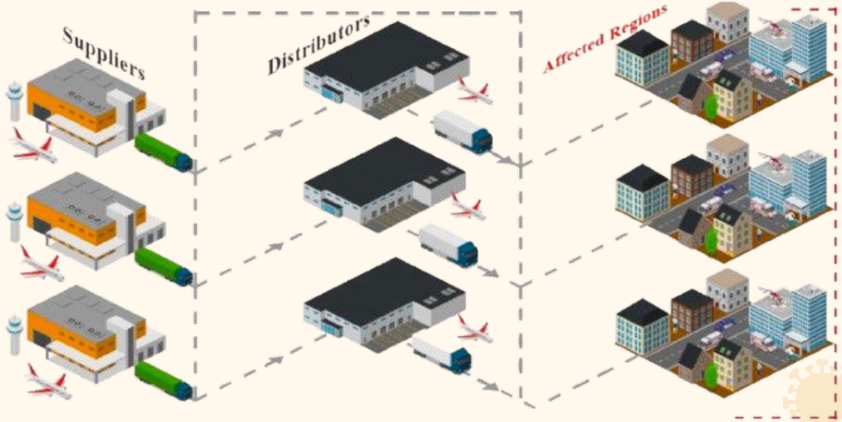
J: index for distributors ($j = 1, 2, \ldots, J$)

K: index for affected regions ($k = 1, 2, \ldots, K$)

V: index for refrigerated truck type v ($v = 1, 2, \ldots, V$)

V': index for refrigerated truck type v' ($v' = 1, 2, \ldots, V'$)

T: index for periods ($t = 1, 2, \ldots, T$)



Assumptions:

1. There are different type of refrigerated trucks, each of which can ship different amount of vaccines to the distributors and ARs (transportation mode is allowed).

2. There is no bound on the number of refrigerated trucks and all available routes are accessible.

3. The production capacity of each supplier is restricted.

4. Because of the crisis and excess global demand, shortage is not allowed.

5. Each distributor can serve more than one AR.

Assumptions:

6. Suppliers can serve each distributor; moreover, they can serve ARs directly.

7. There is multi type of vaccines, each of which is approved by WHO.

8. Each suppliers can produce one type of vaccine.

9. No lead time is considered.

10. In each period, the demand of AR is independent and prearranged.

11. The distributors are each managed by a 3PL.

Parameters:

$D_k^t = Demand\ of\ \ k - th\ AR\ in\ period\ t$

$C_{ij}^{v} = Cold\ transportation\ cost\ per\ unit\ of\ \ vaccine\ by\ ref\ rigerated\ truck\ v\ f\ rom\ supplier\ i\ to\ distributor\ j$

$C_{jk}^{v'} = Cold\ transportation\ cost\ per\ unit\ of\ \ vaccine\ by\ ref\ rigerated\ truck\ v'\ f\ rom\ distributor\ j\ to\ k - th\ AR$

$C_{ik}^{v} = Cold\ transportation\ cost\ per\ unit\ of\ \ vaccine\ by\ ref\ rigerated\ truck\ v\ f\ rom\ supplier\ i\ to\ k - th\ AR$

$C_{v} = Fixed\ cost\ of\ \ utilizing\ ref\ rigerated\ truck\ v$

$C_{v'} = Fixed\ cost\ of\ \ utilizing\ ref\ rigerated\ truck\ v'$

$H_{j} = Average\ inventory\ cost\ of\ \ vaccine\ satdistributor\ j$

Parameters:

$P_k = Penalty\ cost\ of\ unmet\ demand\ at\ AR\ k$

$\mathrm{M} = \mathrm{A\ large\ custom\ number\ (\ big - M\ constant)}$

$PC_i = Maximum\ production\ capacity\ of\ supplier\ i$

$S_j = Maximum\ storage\ capacity\ of\ distributor\ j$

$\alpha = Consumption\ coefficient\ of\ each\ vehicle's\ storage\ capacity\ to\ transport\ each\ box\ of\ vaccine$

$CAP_v = Capacity\ of\ vehicle\ type\ v\ for\ transferring\ boxes\ of\ vaccine\ from\ supplier\ to\ distributor\ and\ AR$

$CAP_{v'} = Capacity\ of\ vehicle\ type\ v'\ for\ transferring\ boxes\ of\ vaccine\ from\ distributor\ to\ AR$

Variables:

x_{ij}^{vt} = Amount of vaccines transported by vehicle v from supplier i to distributor j in period t

$x_{jk}^{v't}$ = Amount of vaccines transported by vehicle v' from distributor j to AR k in period t

x_{ik}^{vt} = Amount of vaccines transported directly by vehicle v from supplier i to AR k in period t

$y_v^t = 1$, if vehicle v delivers vaccine from supplier i to distributor j in period t; 0 otherwise

$y'^t_v = 1$, if vehicle v delivers vaccine from supplier i to AR k in period t; 0 otherwise

$y''^t_{v'} = 1$, if vehicle v' delivers vaccine from distributor j to AR k in period t; 0 otherwise

$z_k^t = 1$, if AR k is supplied in period t; 0 otherwise

R_k^t = Unmet demand at AR k in period t

Inv_j^t = Average inventory level of vaccines in distributor j inperiod t

Num_i^{vt} = Number of vehicle type v transporting vaccines from supplier i in period t

$Num_j^{v't}$ = Number of vehicle type v' transporting vaccines from distributor j in period t

Objective Function:

$$Min\ Z = \sum_{i,j,v,t} C^{v}_{ij} x^{vt}_{ij} + \sum_{j,k,v',t} C^{v'}_{jk} x^{v't}_{jk} + \sum_{i,k,v',t} C^{v}_{ik} x^{vt}_{ik}$$
$$+ \sum_{v,t} C_{v} y^{vt}_{ij} + \sum_{v,t} C_{v} y^{vt}_{ik} + \sum_{v',t} C_{n} y^{v't}_{jk}$$
$$+ \sum_{k,t} P_{k} R^{t}_{k} + \sum_{j,t} HInv^{t}_{j} + deprivation\ cost$$

$$deprivation\ cost = \sum_{t} r(t) \left[\sum_{k} D^{t}_{k} (1 - z^{t}_{k}) + \sum_{k} z^{t}_{k} \left(D^{t}_{k} - \left(\sum_{i,v} x^{vt}_{ik} + \sum_{j,v'} x^{v't}_{jk} \right) \right) \right]$$

Deprivation Cost:

The economic value assigned to human suffering resulting from the lack of critical goods like food, water, or medicine over time. This cost increases non-linearly with prolonged deprivation.

$$deprivation\ cost = \sum_t r(t)\left[\sum_k D_k^t(1 - z_k^t) + \sum_k z_k^t\left(D_k^t - \left(\sum_{i,v} x_{ik}^{vt} + \sum_{j,v'} x_{jk}^{v't}\right)\right)\right]$$

Where:

- $r(t)$: is a time-dependent weighting function that determines the intensity of deprivation cost at time t (e.g., deprivation becomes more severe in later periods).
- The first term in the brackets captures the total demand that is not supplied at all in period t.
- The second term accounts for the shortfall in delivered vaccines even when a region k receives some supply in period t, but not in full.

Constraints:

2. Distributor Flow Balance: A distributor cannot deliver more vaccines than it receives from suppliers in each time period.

$$(2)\quad \sum_{i,v} x_{ij}^{vt} \geq \sum_{k,v'} x_{jk}^{v't} \quad \forall j,t$$

3. Inventory Balance: The inventory level of each distributor is updated based on incoming shipments, previous inventory, and outgoing deliveries.

$$(3)\quad \sum_{i,v} x_{ij}^{vt} + Inv_j^{t-1} = \sum_{k,v'} x_{jk}^{v't} + Inv_j^t \quad \forall j,t$$

4. Unmet Demand Tracking: The difference between actual demand and received vaccines in each Affected Region (AR) is recorded as unmet demand (shortage).

$$(4)\quad D_k^t - \left(\sum_{j,v'} x_{jk}^{v't} + \sum_{i,v} x_{ik}^{vt}\right) = R_k^t \quad \forall t,k$$

Constraints:

5. Storage Capacity Constraint: The total vaccines held at any distributor must not exceed its maximum storage capacity.

$$(5)\quad \sum_{i,v} x_{ij}^{vt} + Inv_j^t \leq S_j \quad \forall j, t$$

6–8. Transportation Activation: Vaccines can only be transported through a route if the corresponding transport vehicle is activated (binary variable = 1). Otherwise, no shipment is allowed.

$$(6)\quad \sum_{i,j} x_{ij}^{vt} \leq My_v^t \quad \forall v, t$$

$$(7)\quad \sum_{i,k} x_{ik}^{vt} \leq My'^{t}_{v} \quad \forall v, t$$

$$(8)\quad \sum_{j,k} x_{jk}^{v't} \leq My''^{t}_{v'} \quad \forall v', t$$

Constraints:

9. Supplier Production Limit: Each supplier can only ship vaccines up to its maximum production capacity per time period—whether to distributors or directly to ARs.

$$(9)\quad \sum_{i,j,v} x_{ij}^{vt} + \sum_{i,k,v} x_{ik}^{vt} \le PC_i \quad \forall t$$

10. ensures that vaccines can only be delivered to an affected region k in period t if the binary variable $z_k^t = 1$. This acts as an activation constraint that prevents delivery unless the region is marked as active.

$$(10)\quad \sum_{i,v} x_{ik}^{vt} + \sum_{j,v'} x_{jk}^{v't} \le M z_k^t \quad \forall k, t$$

11. Backlog Propagation: If demand is not fully met in one period, the remaining shortage is carried over to the next period for future fulfillment.

$$(11)\quad D_k^t + R_k^{t-1} = \sum_{j,v'} x_{jk}^{v't} + \sum_{i,v} x_{ik}^{vt} + R_k^t \quad \forall k, t$$

Constraints:

12. Final Period Fulfillment: All remaining unmet demands must be fully satisfied by the last period of the planning horizon.

$$(12)\quad \sum_{j,v'} x_{jk}^{v'T} + \sum_{i,v} x_{ik}^{vT} = D_k^T + R_k^T \quad \forall k$$

13–14. Vehicle Capacity Constraints: The total volume shipped by each vehicle type must not exceed the available transport capacity—both from suppliers and distributors.

$$(13)\quad a \cdot \left(\sum_{i,j,t} x_{ij}^{vt} + \sum_{i,k,t} x_{ik}^{vt} \right) \leq \sum_{i,t} Num_i^{vt} \cdot Cap_v \quad \forall v$$

$$(14)\quad a \cdot \sum_{j,k,t} x_{jk}^{v't} \leq \sum_{j,t} Num_j^{v't} \cdot Cap_{v'} \quad \forall v'$$

Constraints:

15. Equity Constraint: The difference in supply-to-demand ratios between any two ARs must remain below a specified threshold, ensuring fairness in allocation.

$$(15)\quad \left| \frac{\sum_{i,v} x_{ik}^{vt} + \sum_{j,v'} x_{jk}^{v't}}{D_k^t} - \frac{\sum_{i,v} x_{ik'}^{vt} + \sum_{j,v'} x_{jk'}^{v't}}{D_{k'}^t} \right| \leq \lambda \quad \forall k, k', t$$

16. Variable Type Restrictions: Some variables are integers (e.g., vaccine quantity, number of vehicles), while others are binary (e.g., route activation or not).

$$(16)\ x_{ij}^{vt},\ x_{jk}^{v't},\ x_{ik}^{vt},\ R_k^t,\ Inv_j^t,\ Num_i^{vt},\ Num_j^{v't} \in \mathbb{N} \quad \forall i,j,k,v,v',t \quad y_{v'}^t,\ y_{v''}^t,\ z_k^t \in \{0,\ 1\}$$

04

Experimental results

Case study: Europe

Data and Case study Specification

- Based on the actual data on vaccine distribution in Europe.
- Encompass parts of Europe where pharmaceutical factories are.
- The population of the countries, their need of COVID-19 vaccine, the distance between the suppliers, distributors, and consumers and finally cost parameters of transportation is specified.
- Due to anticipating different situation in a pandemic different scenarios are examined.
- Each scenario changed only one parameter.

Why Europe?

As the COVID-19 is a pandemic, continental europe with several countries with different population would be very useful. It has some good benefits compared to other part of the world:

1. Presence of different vaccine production factories in case of comprehensive study from the supplier to the consumer.
2. There may be fewer countries with a smaller population in a geographical region rather than europe.

It is also worth mentioning that this model can:

1. Adapt to different data
2. Scale applicable in critical situations
3. Be used in different geographical locations

Data parameters

1. There are 4 types of vaccine.
2. There are 4 different suppliers.
3. There are 4 different distributors.
4. There are 10 different ARs.
5. Each period includes 15 days, primary scenario has 6 periods.
6. It is assumed all vaccines are doubled-dose, except johnson and johnson which is single dose.
7. The refrigerated trucks have 40 ft refrigerated containers.
8. Suppliers possess 8 “v” type truck.
9. Distributors possess 20 “v” type truck.
10. Vaccines are preserved in the special boxes holding up to 4875 doses.
11. The weight of the special boxes is 80 pound.

Data parameters

Table 2
The needed parameter values of case study.

Parameter	Value
α	6 cubic foot
PC_i	Uniform (50000,60000)
S_j	Uniform (5000,6000)
C_v	Uniform (100,110)
$C_{v'}$	Uniform (50,60)
H_j	Uniform (0.7,1.3)
P_k	Uniform (30,35)
CAP_v	Uniform (350,360)
$CAP_{v'}$	Uniform (320,350)

Data parameters

Table 3
The positions of suppliers and distributors.

Pharmaceutical companies	Suppliers	Distributors
AstraZeneca	United kingdom	United kingdom
Pfizer	Germany	Germany
Johnson and Johnson	Netherland	Netherland
Moderna	Switzerland	Switzerland

Data parameters

Table 4
The positions of ARs and vaccine demands.

ARs	Population (million)	Demand (million doses)	Demand (boxes)
United kingdom	66.65	133.3	27344
Germany	83.02	166.04	34060
Netherland	17.28	34.56	7090
Switzerland	8.545	17.09	3506
Sweden	10.23	20.46	4197
Italy	60.36	120.72	24764
Spain	46.94	93.88	19258
Greece	10.72	21.44	4398
Poland	17.28	34.56	7090
Austria	8.859	17.718	3635

Data parameters

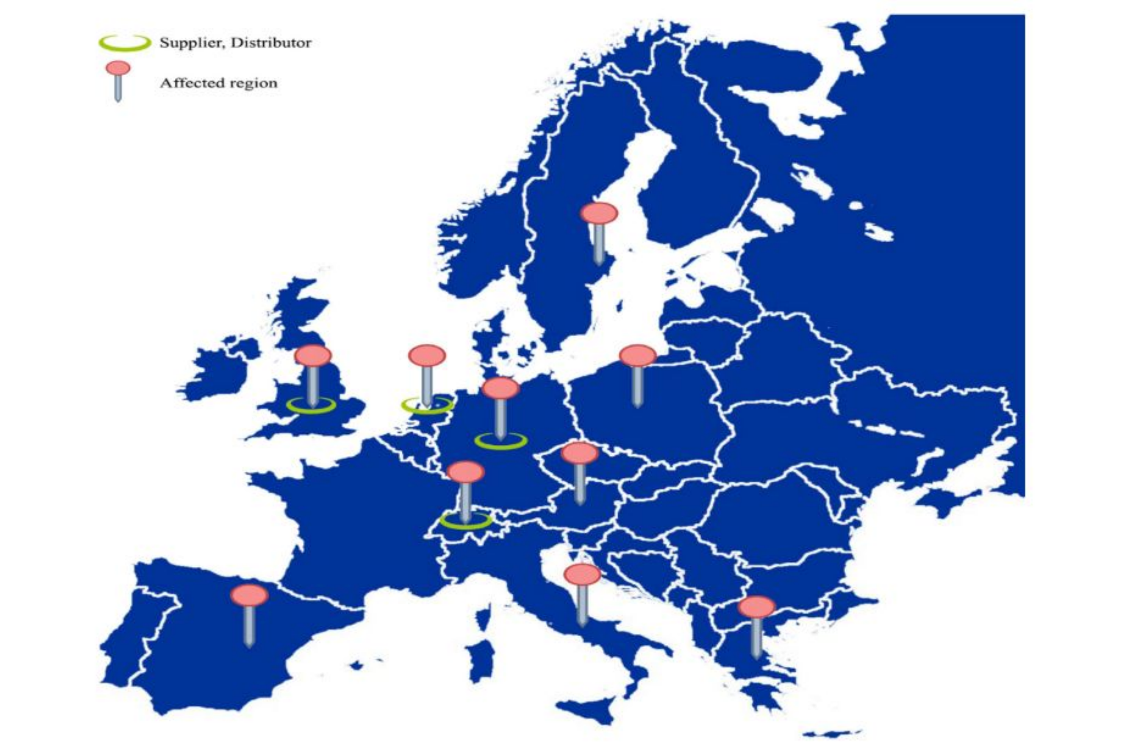


Fig. 2. The location of suppliers, distributors and ARs.

Cost Calculation in this data

The shipping cost in proposed model：

$$\sum_{i.j.v.t} C_{ij}^{v} x_{ij}^{vt} + \sum_{j.k.v'.t} C_{jk}^{v'} x_{jk}^{v't} + \sum_{i.k.v'.t} C_{ik}^{v} x_{ik}^{vt}$$

The way C is calculated：

$$\mathbf{C = distance\ per\ km \times cold\ transportation\ cost\ per\ km\ \times cold\ transportation\ cost\ per\ box}$$

$$\mathbf{Transportation\ cost\ per\ box\ = shipping\ box\ weight \times cold\ transportation\ cost\ per\ pond}$$

Primary Results

Table 5
The primary results.

Total cost	2,221,811,425 €
Deprivation cost	109,668 €
Penalty cost of unmet demand	3,240,893 €
Inventory holding cost	0 €

Some other key points：

1. **The model used all refrigerator trucks.**
2. **The cost of deprivation is only 0.005% of the total cost.**
3. **This result is for 659,768 million doses of vaccine.**

Different Scenarios

First

Increased the time to 10p

Second

Decreased the time to 3p

Third

10% increase in production capacity

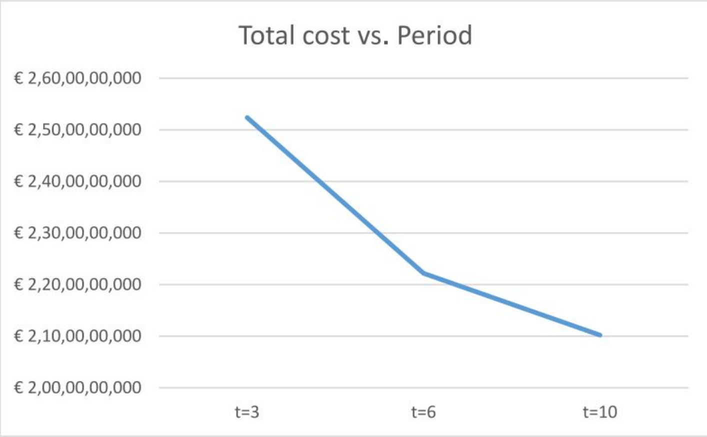
Fourth

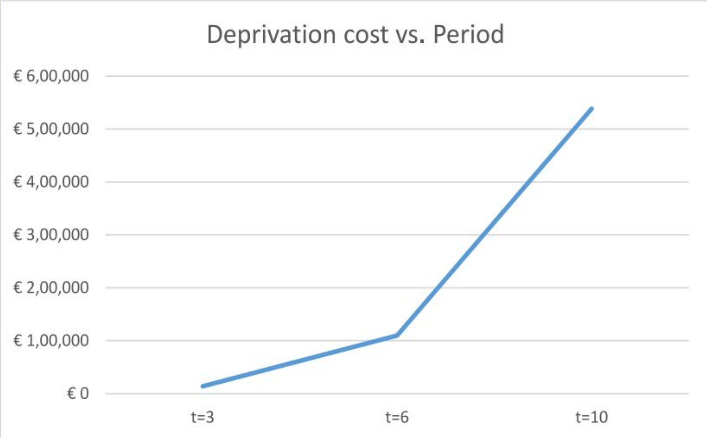
50% increase in demand

Scenarios Results

Table 6
The results of different scenarios.

Scenarios	Different parameters	Total cost	Deprivation cost	Penalty cost of unmet demand
Scenario #1	t = 10	€ 2,102,025,288	€ 538,493	€ 3,017,629
Scenario #2	t = 3	€ 2,523,858,043	€ 13,801	€ 2,629,273
Scenario #3	PC = (55000,65000)	€ 2,221,811,407	€ 109,675	€ 3,240,881
Scenario #4	D*1.5	€ 4,016,280,673	€ 173,290	€ 3,620,366





05

Sensitivity Analysis

Sensitivity analysis approaches

Changing the value of λ

- Paying more attention to equity by decreasing λ
- Neglecting the equity by increasing λ

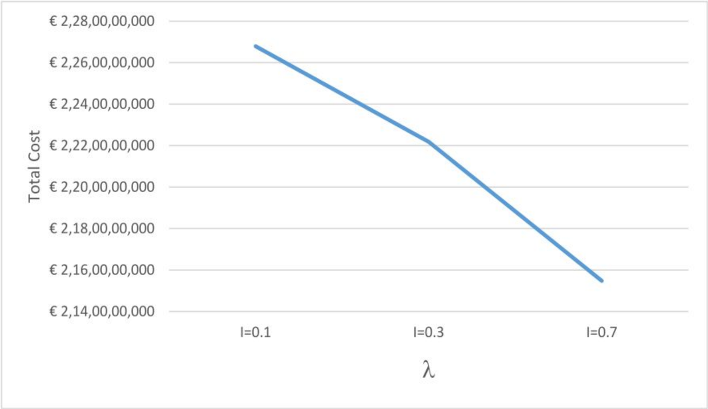
Removing equity constraint

- The model is run with primary data and without restrictions on equity

Different values of λ

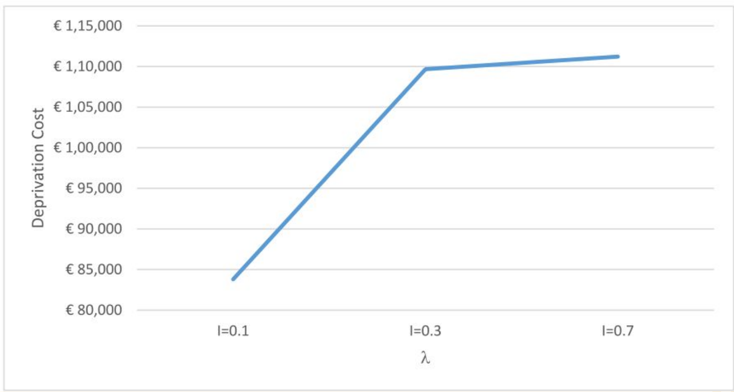
- The impact on total cost:

  Less attention to equity would decrease the total costs



- The impact on deprivation cost:

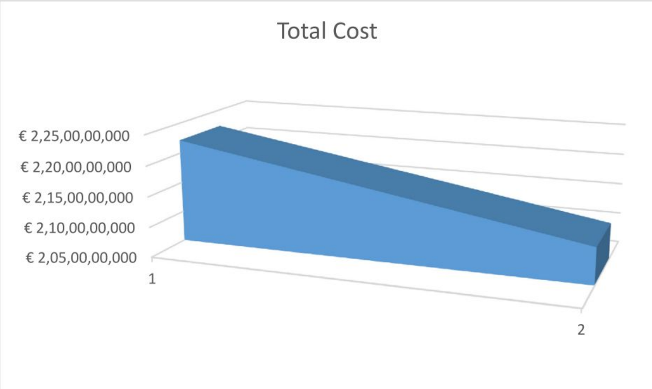
  Slower ARs demand fulfillment increase the deprivation cost



Removing equity constraint

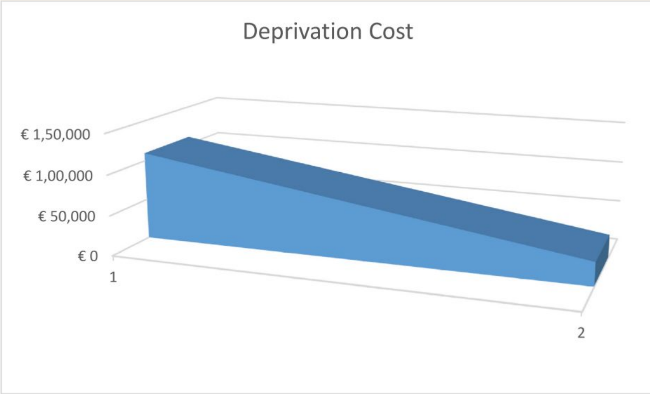
- The impact on total cost:

  Less attention to equity would decrease the total costs



- The impact on deprivation cost:

  Faster ARs demand fulfillment decrease the deprivation cost



Final results

1. Changing the λ

- Decreasing: total cost increased by 2.07% and deprivation cost decreased by 23.59%
- Increasing: total cost decreased by 3.01% and deprivation cost increased by 1.41%

Table 7
The result of changing by the value of λ.

l	Total cost	Deprivation cost
0.1	€ 2,267,924,137	€ 83,796
0.3	€ 2,221,811,425	€ 109,668
0.7	€ 2,154,778,408	€ 111,219

2. Equity constraint

- With: the primary model
- Without: total cost decreased by 5.05% and deprivation cost decreased by 73.8%

Table 8
The result of with/without the equity constraint.

Total cost	Deprivation cost
€ 2,221,811,425	€ 109,668
€ 2,109,483,829	€ 28,731

Managerial insights

1. Fair vaccine coverage in pandemic conditions is a lofty goal to reduce the rate of infection and mortality, and prevent additional cost in the future.

2. The two concepts of equity and deprivation are interdependent.

3. A proper plan reduces the social costs even if other costs such as logistics increase.

4. Managers should focus on Fast Maximum Coverage.

5. As the monitoring over equal vaccine distribution reduces, total cost decrease and deprivation cost increase.

06

Conclusions

Key Finding of the Study:

1. Deprivation Cost Matters, Even if Small

- Although the deprivation cost is a small fraction of total cost, it plays a critical role.
- Addressing deprivation helps prevent future societal costs, such as medical treatment for underserved populations.

2. Time Horizon Has the Greatest Impact

- Extending the planning horizon reduces deprivation, but delays in supply drastically increase social cost.
- Conversely, shorter time horizons raise transport costs but significantly reduce deprivation-related harm.

Limitations:

Lack of access to real-world data

Deterministic assumptions used for parameters.

Future Research:

- Consider uncertainty (stochastic models)
- Objective Function
- Incorporating Real-Time Data
- Advanced Equity Metrics
- Network Disruption and Risk Management

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Do you have any questions?

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