Epidemics logistics

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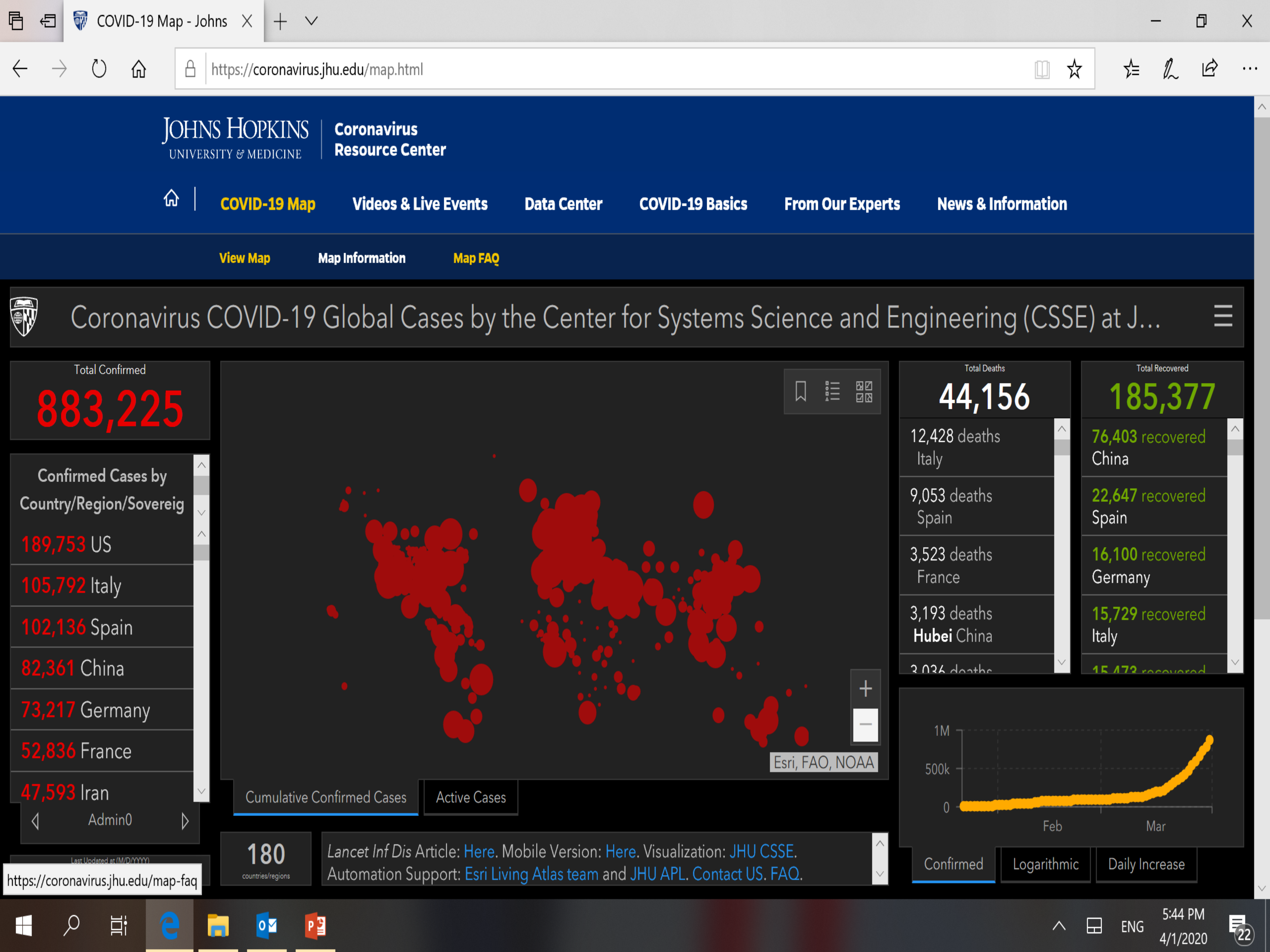


Coronavirus COVID-19 Global Cases by the Center for Systems Science and Engineering (CSSE) at J...

Total Confirmed
883,225

Confirmed Cases by Country/Region/Sovereig

189,753	US
105,792	Italy
102,136	Spain
82,361	China
73,217	Germany
52,836	France
47,593	Iran

180
countries/regions

Lancet Inf Dis Article: Here. Mobile Version: Here. Visualization: JHU CSSE. Automation Support: Esri Living Atlas team and JHU APL. Contact US. FAQ.

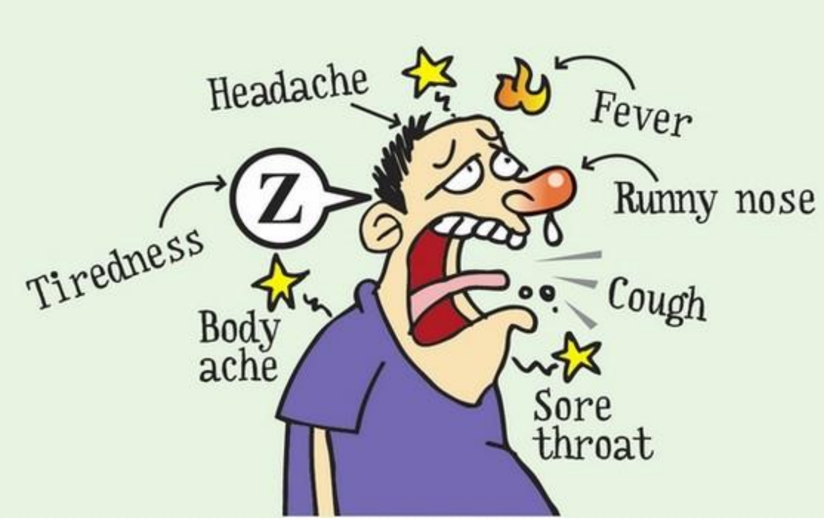
Total Deaths
44,156

12,428 deaths	Italy
9,053 deaths	Spain
3,523 deaths	France
3,193 deaths	**Hubei** China
3,036 deaths	

Total Recovered
185,377

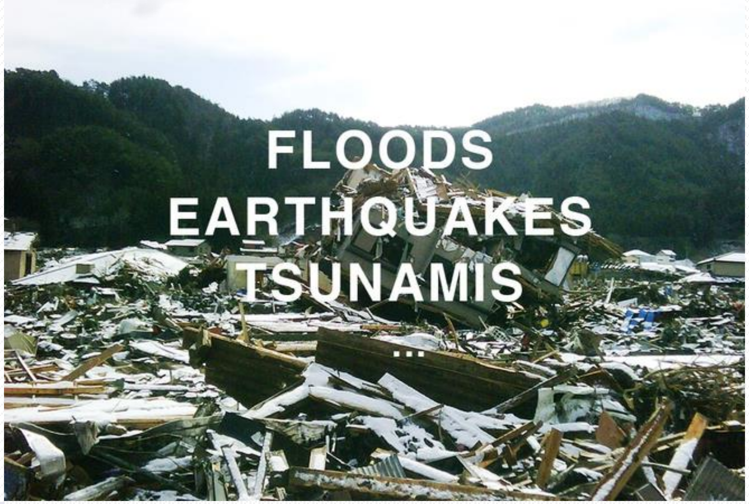
76,403 recovered	China
22,647 recovered	Spain
16,100 recovered	Germany
15,729 recovered	Italy
15,473 recovered	

Introduction



natural causes (e.g. influenza outbreak)

deliberate terrorist actions (bioterrorism)



natural disasters

man-made disasters

Introduction

"Nothing for you to worry about. We're cleaning students' lockers."

Containment of an outbreak:

- Non-pharmaceutical interventions
- Pharmaceutical interventions
- Harmonized approaches.

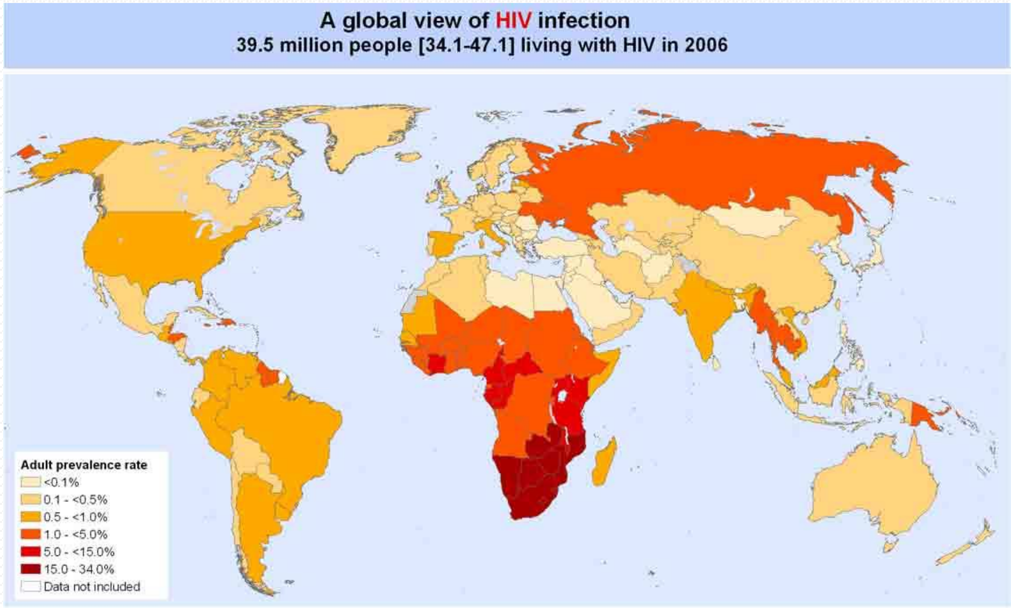
The containment effort consists of four **phases**:
Preparedness - Outbreak investigation – Response - Evaluation

Epidemics control and logistics operations: Preparedness

- Maintaining a certain level of available resources so as to reduce morbidity and mortality when an outbreak occurs
- Pharmaceuticals and supplies in large quantities in order to assist a prompt response, if necessary
- Procurement of vaccines and medical supplies and their exact storing location play a crucial role.

Epidemics control and logistics operations: Outbreak investigation

- Detection of any suspected outbreak and its confirmation through laboratory testing.
- Surveillance systems must be placed to provide the essential information regarding any unexplained infection increases seen over a period of time.
- Determine the type and magnitude of the containment effort once epidemic thresholds have been reached.



The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of the World Health Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted lines on maps represent approximate border lines for which there may not yet be full agreement.

Data Source: WHO / UNAIDS
Map Production: Public Health Mapping and GIS
Communicable Diseases (CDS)
World Health Organization

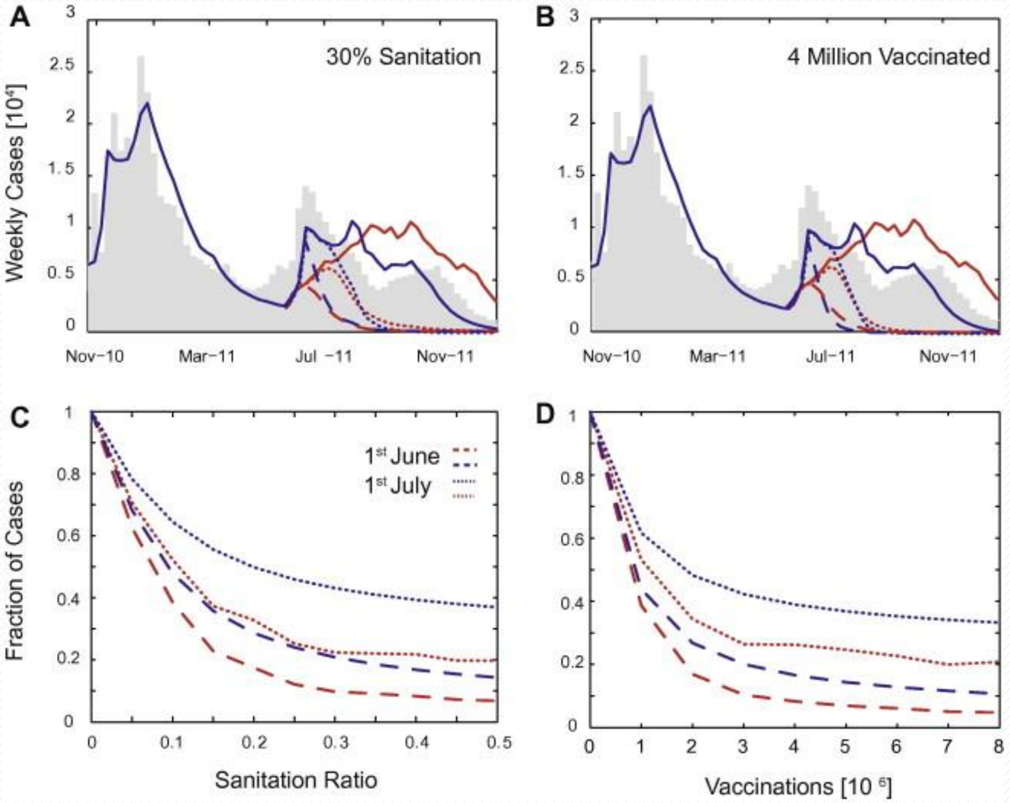
World Health Organization

Epidemics control and logistics operations: Response

- Once an epidemic outbreak is confirmed, measures and control strategies must be implemented as soon as possible at a regional and/or national level.
- Treatment centers should be established and available resources such as medical supplies and personnel should be deployed rapidly in order to contain the epidemic.

Epidemics control and logistics operations: Evaluation

- The evaluation phase is very useful as it provides strong insights towards a series of modifications that need to be made in order to increase the resilience of the control mechanisms in future epidemic outbreaks.
- Despite the fact that the evaluation phase entails limited physical movement of medical supplies and complementary commodities, it remains important from a logistical point of view.



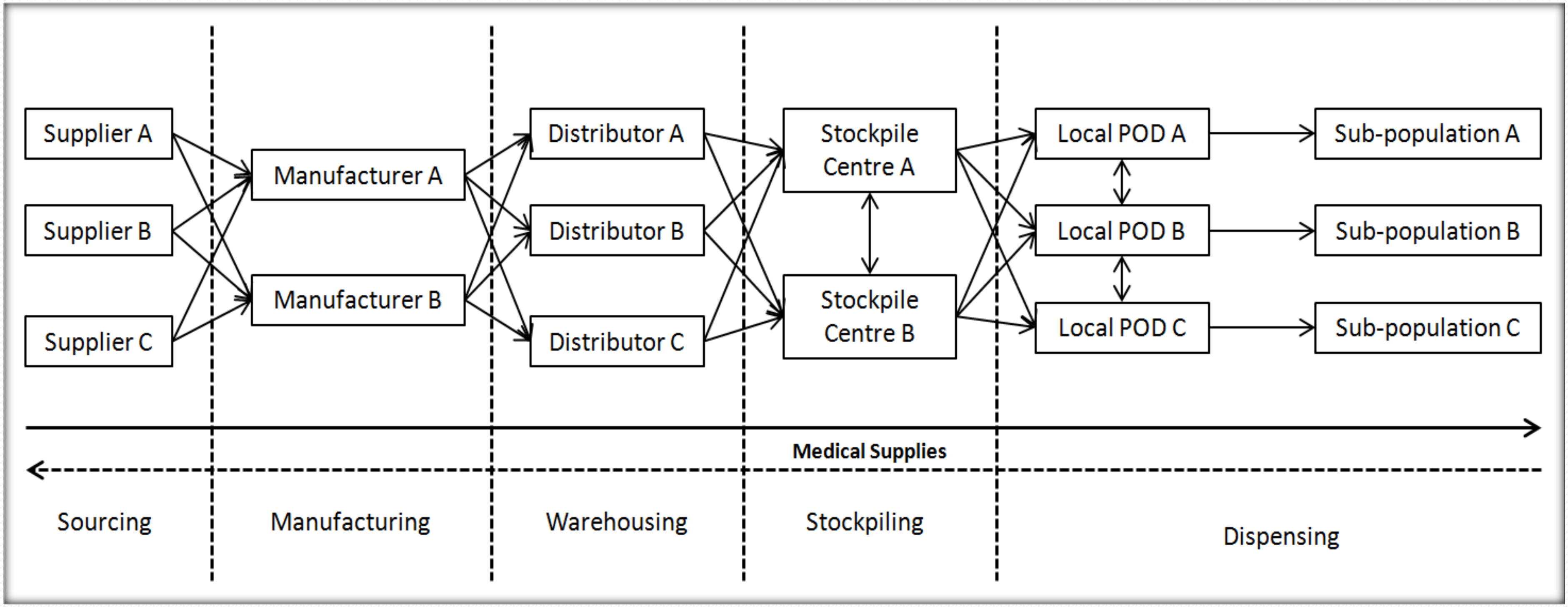
Epidemics control and logistics operations: Actions

- Establish an **emergency supply chain**
- Manufacturers should produce vaccines, antiretroviral drugs and complementary medical supplies
- Governments and public health institutions should purchase and stockpile well in advance
- Transportation and distribution of these supplies from central warehouses to regional store sites and then to local Points of Dispensing (PODs).

Epidemics control and logistics operations: Managerial issues

- Affected people proceeding to treatment centers - patient flow operations - dispensing activities of the medical supplies
- Reverse logistics activities (dangerous wastes must be treated carefully or disposed)
- Coordination among manufacturers, governments, primary health care institutes, possibly military agencies, NGOs, etc.
- Managing the information regarding the demand for medical supplies as well as the flow of funds.

Epidemics control and logistics operations: Materials Flow (Dasaklis et al., 2012)



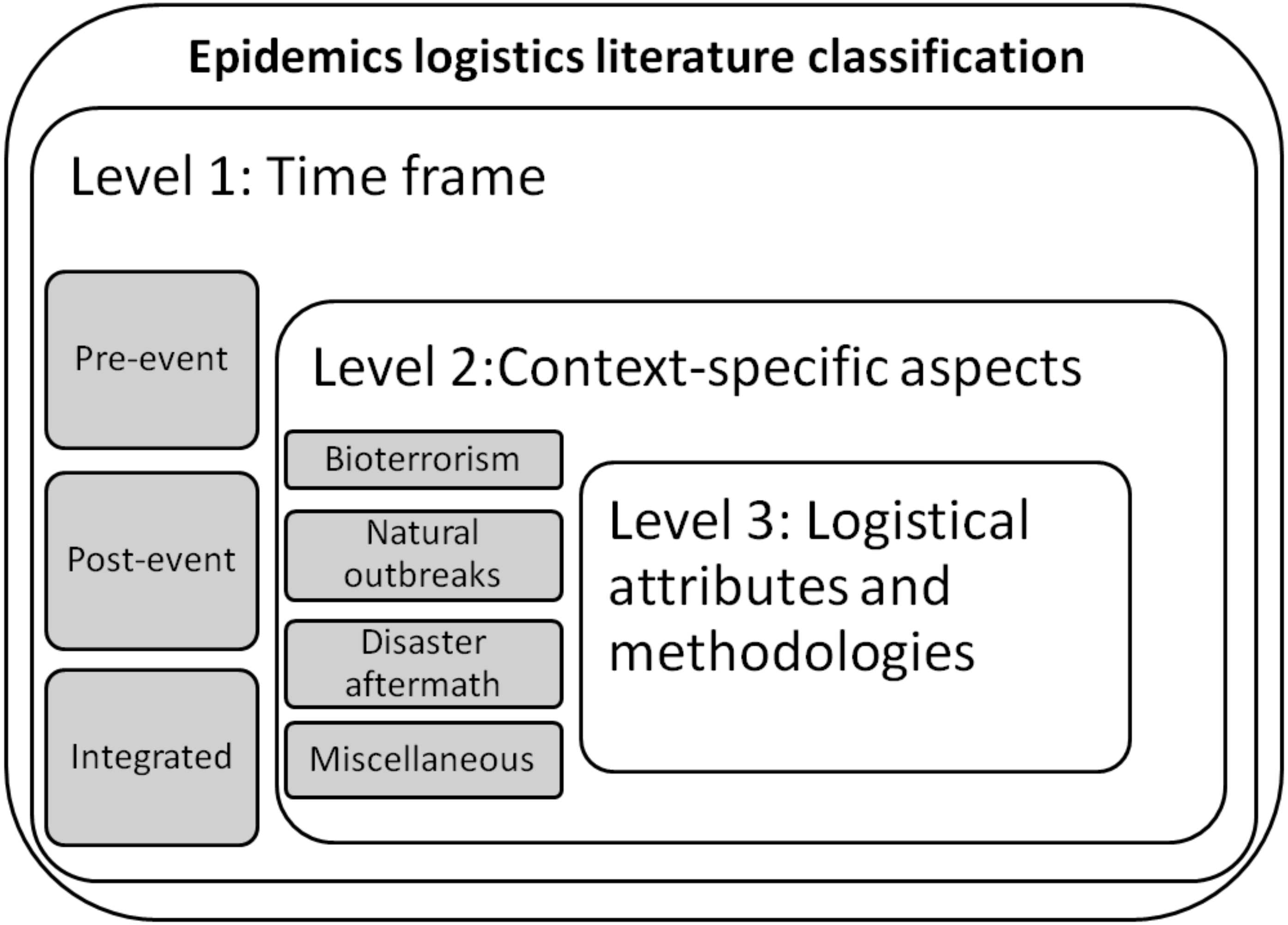
Materials flow of the epidemics control supply chain (End-to-End approach).

Literature review

Classification based on a three-level assessment framework:

- First level: the various logistical features incorporated in each reference are classified according to the time framework in which they take place (pre-event or post-event)
- Second level: a context-specific classification is made where the logistics features are correlated to the nature of the outbreak
- Third level: the logistical features and the methodologies applied (qualitative or quantitative) for solving the problem tackled are classified.

Literature review



Epidemics logistics literature classification

Level 1: Time frame

- Pre-event
- Post-event
- Integrated

Level 2:Context-specific aspects

- Bioterrorism
- Natural outbreaks
- Disaster aftermath
- Miscellaneous

Level 3: Logistical attributes and methodologies

A framework for epidemics logistics literature classification.

Literature review

Facts:

- Epidemic control measures may vary depending on the nature of the outbreak and their implementation time horizon
- Communicable disease outbreaks may also occur in the aftermath of natural disasters where certain sub-populations are dislocated or subject to a humanitarian crisis
- Disease outbreaks may also occur during big events and mass gatherings such as the Olympic Games
- The time frame in which control measures apply may also be different.

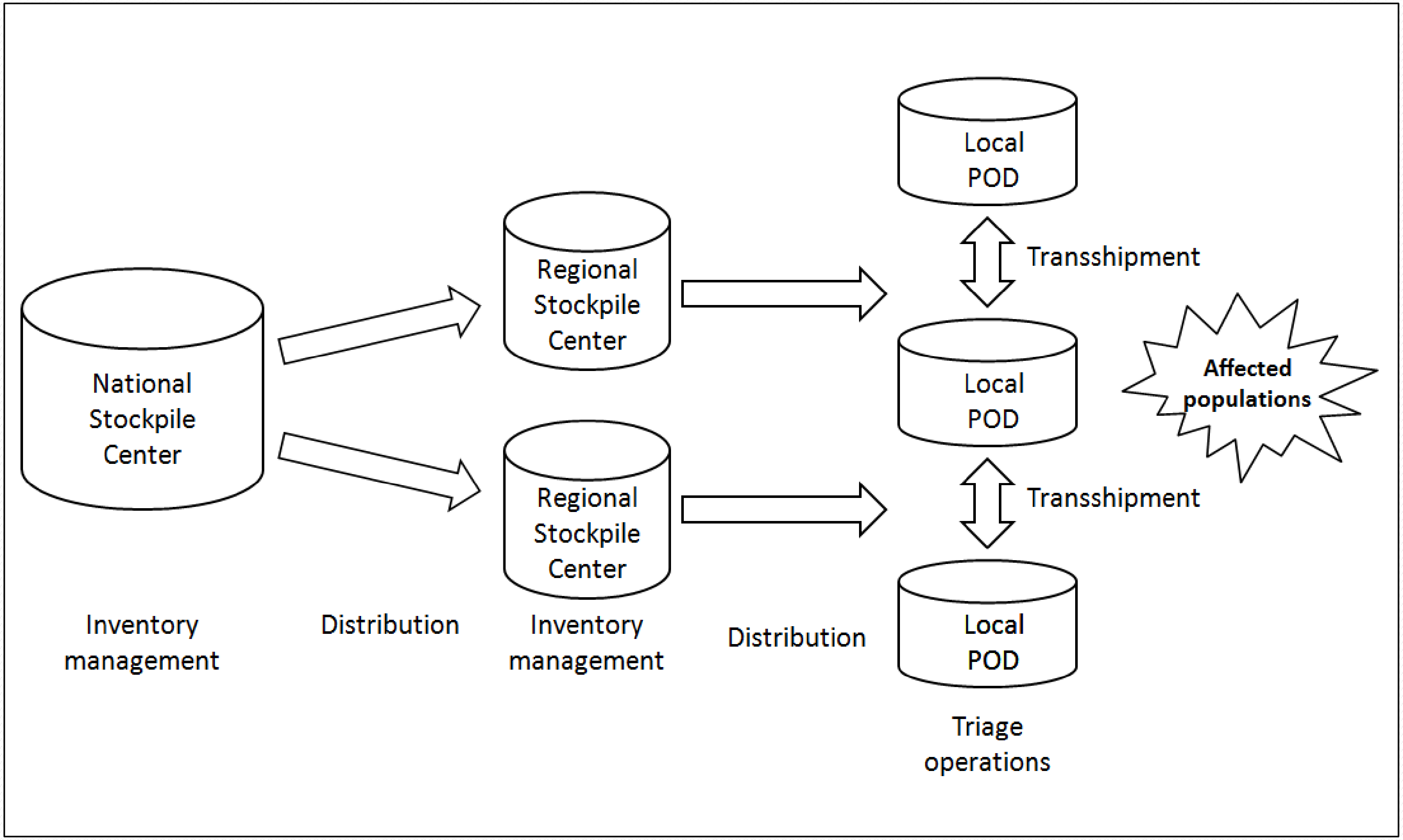
Literature review: Essential question

How and to what extent the availability of certain quantities of essential medical supplies (vaccines) could affect the progression of a disease outbreak?

Need to define:

- the amount of commodities to be utilized during the control effort
- the selection of modes of transportation/distribution and relevant capacities
- the inventory level of medical supplies and commodities held in each node (facility) of the network
- the capacity of stockpile centers (National, Regional and Local)

Literature review: Epidemics control network



Epidemics control logistics network configuration.

OR/MS contribution to resources' allocation and scheduling for epidemics control

Problems:

- Limited resources' allocation among subpopulations
- Scheduling resources for epidemics control
- Etc.

Commonly used objectives:

- Maximize the number of Quality Adjusted Life Years gained
- Maximize the number of infections averted (equivalently minimize the cumulative number of new infections).

Techniques:

- Linear and integer programming models
- Numerical analysis procedures
- Cost-effectiveness analysis
- Simulation
- Non-linear optimization
- Control theory techniques
- Heuristic algorithms.

Problems addressed

1. Controlling infectious disease outbreaks: A deterministic allocation-scheduling model with multiple discrete resources.
2. Emergency supply chain management for controlling a smallpox outbreak: The case for regional mass vaccination.

Multiple resources problem (Rachaniotis et al., 2017)

Find the optimal schedule-allocation of limited discrete resources (mobile medical teams) employed in parallel in a time horizon to implement a vaccination campaign for infected subpopulations unable to proceed to vaccination centres either because they are house bound (elderly, incapacitated etc.) or they are in institutions in several distinct areas in order to minimize the total number of new infections (or, equivalently, to maximize the total number of infections averted).

Assumptions

- The mobile medical teams can be considered as parallel (identical or non-identical) unrelated resources with constant service rates
- More than one medical team may be allocated to a specific regional population
- Pre-emption is not allowed
- Control actions rely on vaccination of specific groups of the population (house bound, institutionalized etc.)
- All the available medical teams at any time are employed for controlling the epidemic
- The resources’ traveling times are assumed to be negligible.

Notation and objective

Let:

$\mathbf{P}=\{P_1,P_2,\ldots,P_n\}$ be the set of n populations in different regions, and let N_i be the size of P_i, $i=1,\ldots,n$.

$t_0>0$ be the common for all populations time required for the resources to commence vaccination.

t be the discrete time units (days).

t_{end} be the end of the vaccination campaign in all regions. This time is not known in advance, since it depends on whether additional (resources) medical teams become available and when (time and resource-dependent problem).

m_t be the resources (medical teams) available at time t.

$(r_1(t),r_2(t),\ldots,r_n(t))$ be the vector of the number of medical teams assigned for vaccination in every regional population at time t, where $r_i(t)\in\{0,1,\ldots,m_t\}$, $i=1,\ldots,n$. This is the problem’s decision vector variable.

R_{Ei} be the effective reproduction number in P_i.

$I_i(r_i(t))$ be the number of new infections therefore infective in P_i at time t.

$C(r_i(t))$ be the completion time of the vaccination campaign for controlling the epidemic in P_i at time t (i.e. $R_{Ei}\leq 1$), having $r_i(t)$ medical teams assigned to region i.

The objective is to minimize the total number of new infections, given the available number of mobile medical teams:

$$\min \sum_{t=t_0}^{t_{end}} \sum_{i=1}^{n} I_i(r_i(t))$$

$$s.t. \quad \sum_{i=1}^{n} r_i(t) = m_t, t = t_0, t_0+1, \ldots, t_{end}$$

$$r_i(t) \in \{0,1,\ldots,m_t\}, t = t_0, t_0+1, \ldots, t_{end}$$

The number of new infections at any time instance can be calculated using as input any existing disease transmission model (from compartmental modeling to agent-based modeling approaches).

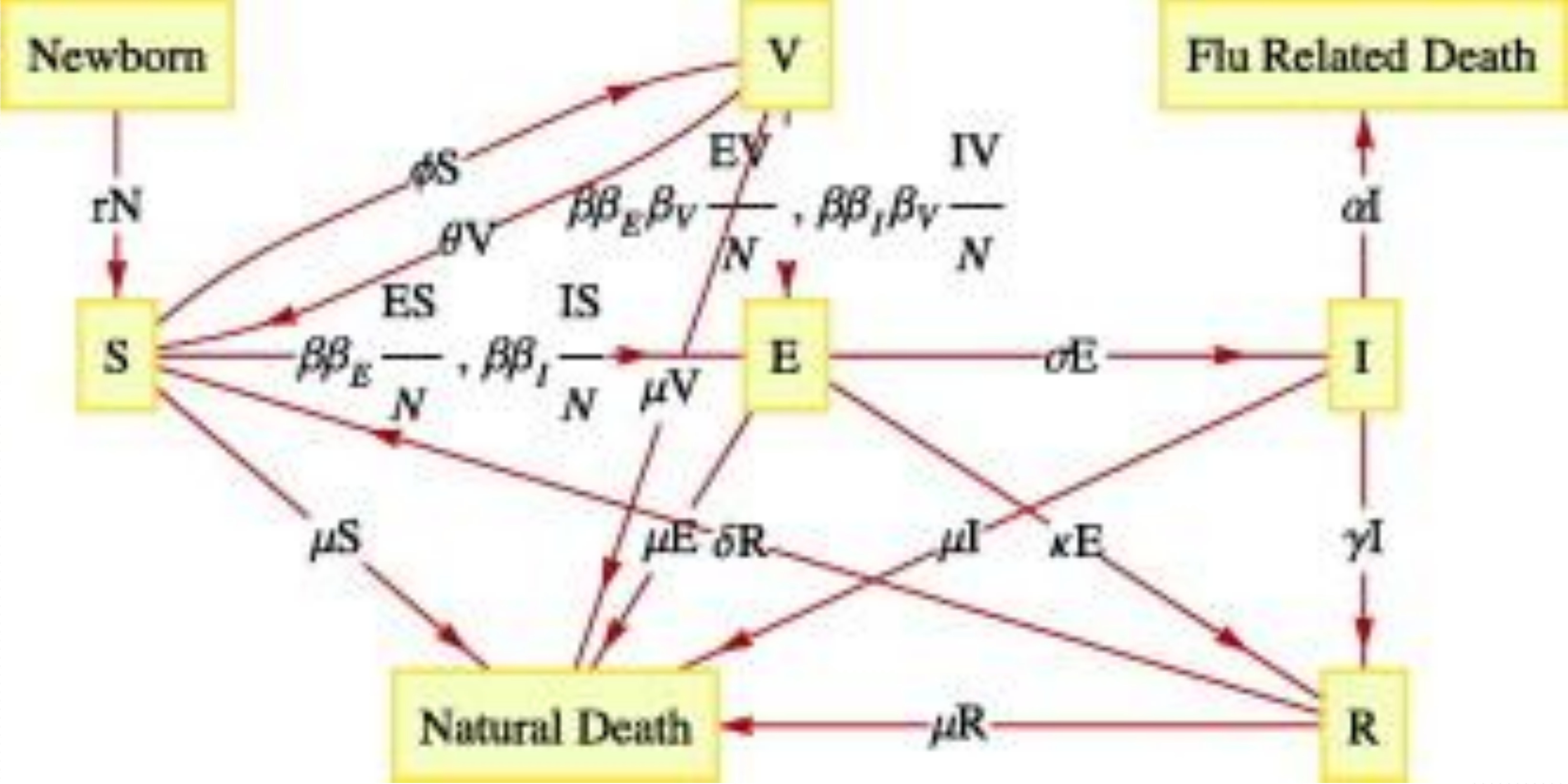
Solution methodology

Step 1: Allocate resources to populations according to the incremental algorithm (Shih, 1974) for solving the respective static discrete resource allocation problem. The vaccination time duration under the current assignment is calculated.

Step 2: Check whether the current resource allocation should be altered. The resource allocation changes in two cases: a) arrival of additional resources, b) the region’s vaccination with the shortest completion time finishes. If yes, move to Step 3. If not, then the vaccination campaign is completed (time t_{end} is reached) and the algorithm ends calculating the total number of infected people.

Step 3: Calculate new populations’ susceptibles numbers and return to Step 1.

Example: A case of influenza in Greece



The SVEIR influenza epidemic model (Samsuzzoha et al., 2012).

Population is divided into five subgroups: susceptible (*S*), vaccinated (*V*), exposed (*E*), infective (*I*) and recovered (*R*).

Model’s parameters

β: Contact rate

β_E: Ability to cause infection by exposed individuals

β_I: Ability to cause infection by infectious individuals

1-β_V: Vaccine effectiveness

σ^{-1}: Mean duration of latency

γ^{-1}: Mean recovery time for clinically ill

δ^{-1}: Duration of immunity loss

μ: Natural mortality rate

r: Birth rate

κ: Recovery rate of latent

α: Flu induced mortality rate

θ^{-1}: Duration of vaccine-induced immunity loss

CSR: the mobile medical teams’ constant service rate

φ_t: Rate of vaccination. It is $\varphi_t = r(t)CSR$, which differs from the common SVEIR models’ assumption that the vaccination rate is constant during the control effort.

Model’s equations

The model is represented by the following system of ordinary differential equations:

$$S'(t) = -\beta\beta_E \frac{ES}{N} - \beta\beta_I \frac{IS}{N} - \varphi_t S - \mu S + \delta R + \theta V + rN$$

$$V'(t) = -\beta\beta_E\beta_V \frac{EV}{N} - \beta\beta_I\beta_V \frac{IV}{N} - \mu V - \theta V + \varphi_t S$$

$$E'(t) = \beta\beta_E \frac{ES}{N} + \beta\beta_I \frac{IS}{N} + \beta\beta_E\beta_V \frac{EV}{N} + \beta\beta_I\beta_V \frac{IV}{N} - (\mu + \kappa + \sigma)E$$

$$I'(t) = \sigma E - (\mu + \alpha + \gamma)I$$

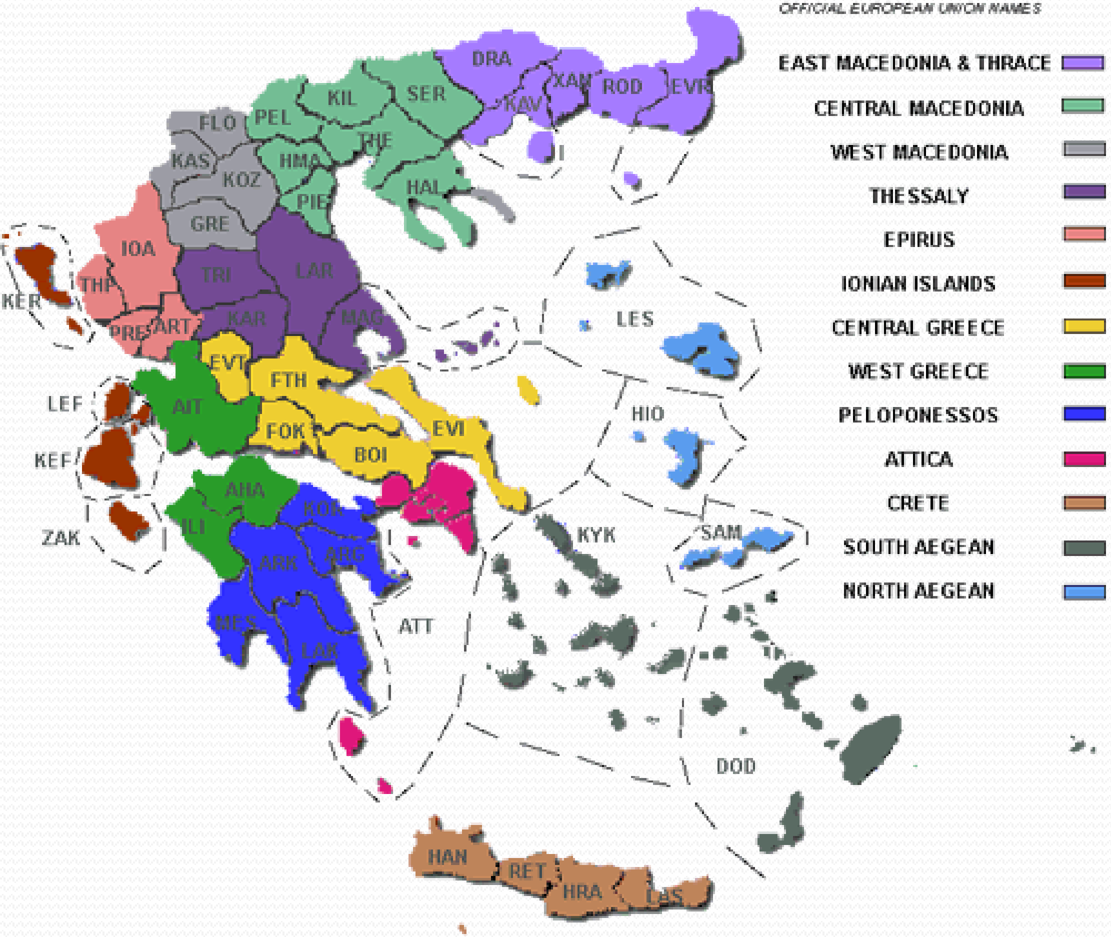
$$R'(t) = \kappa E + \gamma I - \mu R - \delta R$$

The basic reproduction number for the previous model is provided by the next

formula:

$$R_0 = \frac{\beta(r\beta_E + \alpha\beta_E + \gamma\beta_E + \sigma\beta_I)(r + \theta + \beta_V\varphi_t)}{(r + \alpha + \gamma)(r + \kappa + \sigma)(r + \theta + \varphi_t)}$$

Greece’s Health Districts and targeted populations

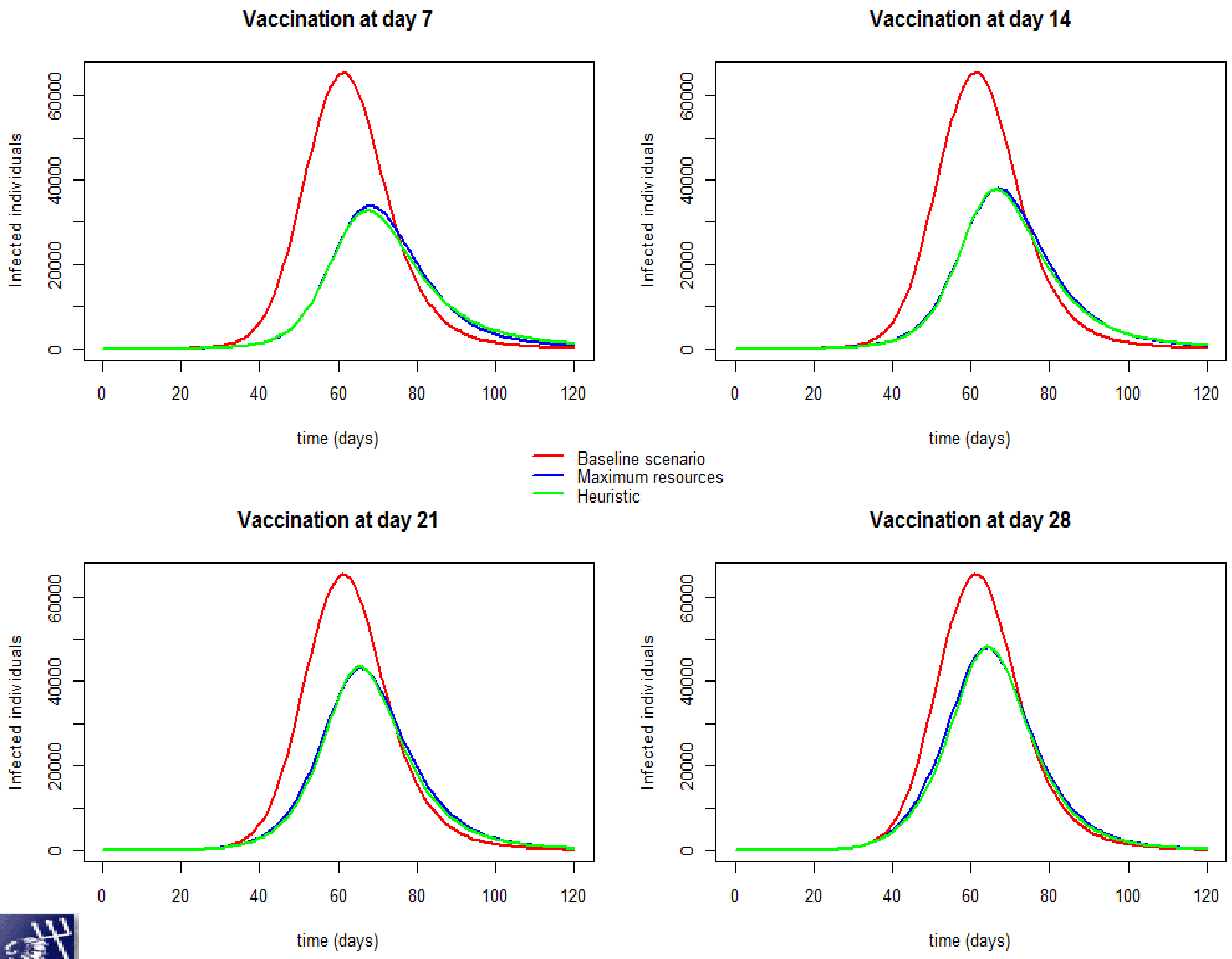


District	Estimated targeted subpopulation
East Macedonia and Thrace	15,000
Central Macedonia	43,000
West Macedonia	9,000
Epirus	14,000
Thessaly	25,000
West Greece	25,000
Central Greece	22,000
Attica	128,000
Peloponnese	28,000
Ionian islands	9,000
North Aegean	10,000
South Aegean	9,000
Crete	25,000

Scenarios and sensitivity analysis

Intervention strategy	Resource allocation policy	Scenario
No intervention	-	Baseline
Reactive mass vaccination starting at day 7, 14, 21, 28 and 60 from the onset of the outbreak	Allocation of a single resource to all sub-populations	Fixed strategy
	Allocation of a constant amount of resources by using the size of each sub-population as the main driver	Maximum resources
	Dynamic reallocation of resources	Heuristic

Results



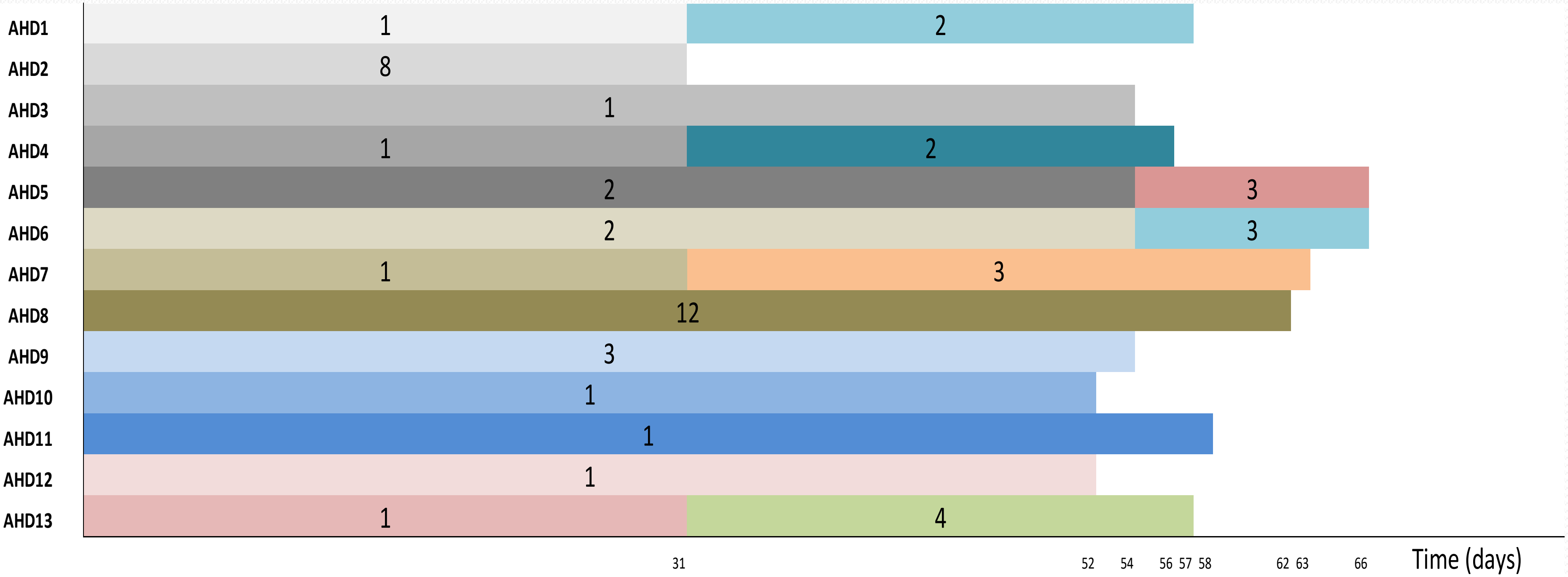
Vaccination at day 7

Vaccination at day 14

Vaccination at day 21

Vaccination at day 28

Results



Heuristic algorithm’s solution Gantt chart for d=7

- The maximum resources scenario outperforms the no vaccination scenario (the percentage difference of total infective cases ranges from 31.8% to 52.7% respectively, increasing when the vaccination campaign initiates earlier).
- The heuristic algorithm’s solution also outperforms the maximum resources scenario where the percentage difference of total infected cases ranges from 1.1% to 2.3% respectively, translated into 15-20 less deaths per 1,000 infective cases averted.

Smallpox outbreak: The case for regional mass vaccination (Dasaklis et al., 2017)

Smallpox is considered one of the most feared bioterrorist agents with a case-fatality rate ranging from 15 to 30%.

Problem's description

Two types of supplies should be transported from a central warehouse to RSCs and then to local PODs:

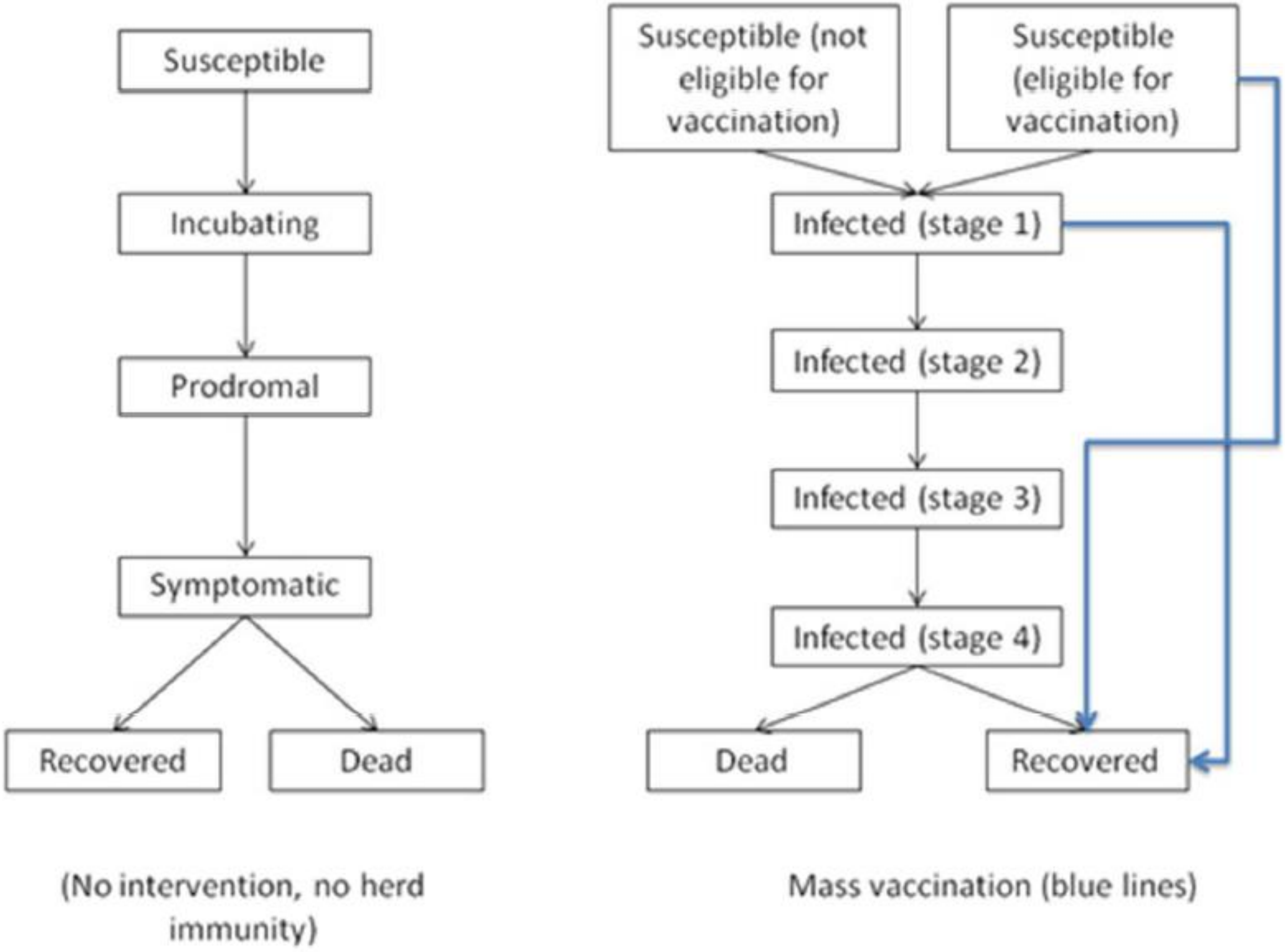
- Crucial medical supplies like vaccines. For these supplies certain transportation protocols should be followed and separate vehicles should be used.
- Vaccine administration supplies (smallpox vaccine coolers/refrigerators, vaccine diluents, sterilized bifurcated needles, etc.), general supplies and equipment (tables, chairs, water and cups, paper, telephones, fax machines etc.) and other emergency supplies (blankets, food meals, etc.). These supplies could be bundled together.

Different types of vehicles (in terms of capacity) and different modes of transportation should be used (according to the type of commodity transported/distributed). The objective is the minimization of the total amount of unsatisfied demand over all types of commodities, final demand points (Points of Dispensing), for all periods.

Problem’s formulation

The modelling approach consists of two parts. The first part is the compartmental modelling approach related to the disease’s progression. The second part relates to the epidemics control logistics network configuration model.

Modelling smallpox's progression



- Infected but asymptomatic, non-infectious, and vaccine-sensitive (I_1)
- Infected but asymptomatic, non-infectious, and vaccine-insensitive (I_2)
- Infected but asymptomatic and infectious (I_3)
- Symptomatic and isolated (I_4).

Notation

Let

T: be the planning horizon.

t: time period (day), t-1,…,T.

C_M: be the set of different essential medical commodities (vaccines)

C_S: be the set of different ancillary supplies (bifurcated needles, food, blankets etc)

C: be the set of commodities in total. It is $C=C_M \cup C_S$

NSC: be the set of National Stockpiling Centres

RSC: be the set of Regional Stockpiling Centres

POD: be the set of local Points of Dispensing

N=NSC+RSC+POD: be the union of nodes in the network

Parameters

Let

$S_{ic}(t)$: be the supply of commodity type c in time period t at the National Stockpiling Centre i, $i \in NSC$, $c \in C$, t=1,…,T

M(t): be the set of kinds of transportation means $\{M_1(t),\ldots, M_K(t)\}$ in time period t, i.e. there are K different kinds (subsets) of non-identical transportation means with $|M_k(t)|$ identical means of each kind, k=1,…,K

V_{kc}: be the capacity of transportation mean k for commodity type c, k=1,…,K, $c \in C$.

v_c: be the volume of commodity type c, $c \in C$

G(N,E): be a graph, where E is the set of edges (i,j,k), $i,j \in N$, k=1,…,K

$d_{ic}(t)$: the demand for commodity type c in time period t at dispensing point i, $i \in POD$, $c \in C$, t=1,…,T

$U_{ik}(t)$: Unloading capacity for the facility in node i for transportation mean of kind k in time period t, $i \in N$, k=1,…,K, t=1,…,T

$SC_i(t)$: Storage capacity for the facility in node i in time period t, $i \in N$, t=1,…,T

$LC_{ik}(t)$: Loading capacity for the facility in node i for transportation mean k in time period t, $i \in N$, k=1,…,K, t=1,…,T

Decision variables

$x_{ijck}(t)$: amount of commodity type c transported from node i to node j by the k-th kind of transportation in period time t, $i,j \in N$, $i \neq j$, $c \in C$, k=1,…,K, t=1,…,T.

$u_{ic}(t)$: unsatisfied demand of commodity type c at node i in period time t, $i \in POD$, $c \in C$, t=1,…,T

$I_{ic}(t)$: Inventory of commodity type c at node i in period time t, $i \in N$, $c \in C$, t=1,…,T

Smallpox progress model equations

$$\frac{dS_1(t)}{dt} = -\beta\, S_1(t) I_3(t)$$

$$\frac{dS_2(t)}{dt} = -\beta\, S_2(t) I_3(t) - v_s \alpha(t) \sum_{i=1}^{n} I_{ic}(t) S_2(t)$$

$$\frac{dI_1(t)}{dt} = \beta\, S_1(t) I_3(t) + \beta\, S_2(t) I_3(t) - r_1 I_1(t) - v_1 \gamma(t) \sum_{i=1}^{n} I_{ic}(t) \mathrm{I}_1(t)$$

$$\frac{dI_2(t)}{dt} = r_1 I_1(t) - r_2 I_2(t)$$

$$\frac{dI_3(t)}{dt} = r_2 I_2(t) - r_3 I_3(t)$$

$$\frac{dI_4(t)}{dt} = r_3 I_3(t) - r_4 I_4(t)$$

$$\frac{dR(t)}{dt} = r_4 I_4(t) + v_s \alpha(t) \sum_{i=1}^{n} I_{ic}(t) S_2(t) + v_1 \gamma(t) \sum_{i=1}^{n} I_{ic}(t) \mathrm{I}_1(t)$$

Smallpox progress model equations

$$\alpha(t) = \frac{S_2(t)}{S_2(t)+I_1(t)+I_2(t)+I_3(t)}$$

$$\gamma(t) = \frac{I_1(t)}{S_2(t)+I_1(t)+I_2(t)+I_3(t)}$$

$$\sum_{i=1}^{n} d_{ic}(t) = \mathrm{S}_2\left(\mathrm{t}\right)+\mathrm{I}_1(t)+\mathrm{I}_2(t)+\mathrm{I}_3(t)$$

As the vaccine provides protection to those susceptible to the disease and to those at stage 1 of infection there will be a quantity $V_w(t)$ of vaccine wasted per period:

$$V_w(t) = \left[\frac{I_2(t)+I_3(t)}{S_2(t)+I_1(t)+I_2(t)+I_3(t)}\right]\sum_{i=1}^{n} I_{ic}(t)$$

Logistics network configuration model

Assumptions:

- NSC, RSC and POD are disjoint sets, e.g. a RSC cannot serve as local POD, etc.
- The time to transfer commodities from a transportation mean to another is considered negligible.
- Travelling times between the two most distanced nodes of the network do not exceed the period of one day (24 hours).

Logistics network configuration model

$$\min \sum_{i\in POD}\sum_{c\in C}\sum_{t=1}^{T} u_{ic}(t)$$

Constraints

$$I_{ic}(t)=I_{ic}(t-1) + S_{ic}(t) - \sum_{j\in RSC}\sum_{k=1}^{K} x_{ijck}(t)\text{, i}\in\text{NSC, c}\in\text{C, t=1,…,T}$$

$$I_{ic}(t)=I_{ic}(t-1) + \sum_{\substack{j\in NSC\\ j\neq i}}\sum_{k=1}^{K} x_{jick}(t) - \sum_{\substack{j\in POD\\ j\neq i}}\sum_{k=1}^{K} x_{ijck}(t)\text{, i}\in\text{RSC, c}\in\text{C, t=1,…,T}$$

$$I_{ic}(t)-u_{ic}(t)=I_{ic}(t-1) - u_{ic}(t-1) - d_{ic}(t) + \sum_{\substack{j\in RSC\\ j\neq i}}\sum_{k=1}^{K} x_{jick}(t)\text{, i}\in\text{POD, c}\in\text{C, t=1,…,}$$

$$\sum_{c\in C} I_{ic}(t) \leq SC_i(t)\text{, i}\in\text{N, t=1,…,T}$$

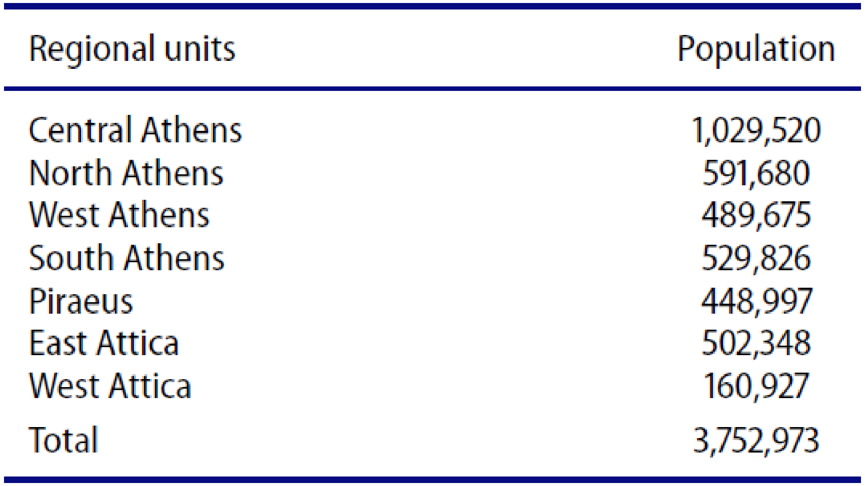
$$\sum_{\substack{i,j\in N\\ i\neq j}} v_c x_{ijck}(t) \leq V_{kc}\left|M_k(t)\right|\text{, k=1,…,K, c}\in\text{C, t=1,…,T}$$

$$\sum_{\substack{j\in RSC+POD\\ j\neq i}}\sum_{c\in C} x_{ijck}(t) \leq LC_{ik}(t)\text{, i}\in\text{N, k=1,…,K, t=1,…,T}$$

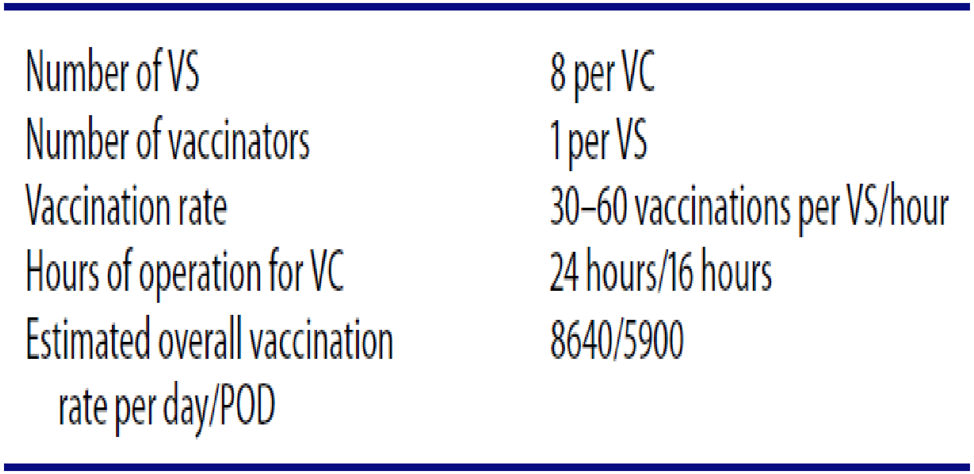
$$\sum_{\substack{j\in N\\ j\neq i}}\sum_{c\in C} x_{jick}(t) \leq UC_{ik}(t)\text{, i}\in\text{RSC+POD, k=1,…,K, t=1,…,T}$$

$x_{ijck}(t), u_{ic}(t), I_{ic}(t)\geq 0$, i, j∈N, c∈C, k=1,…,K, t=1,…,T

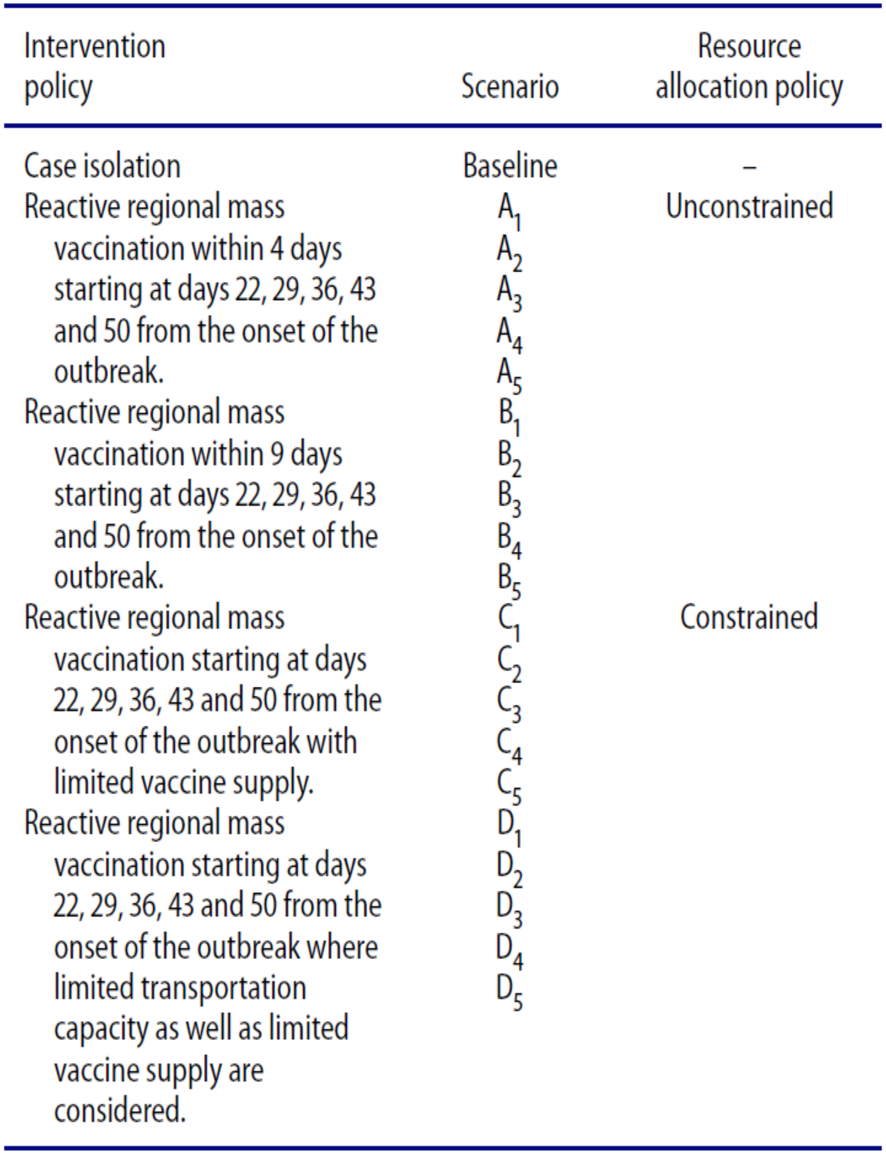
Numerical experiments: Athens



Regional units	Population
Central Athens	1,029,520
North Athens	591,680
West Athens	489,675
South Athens	529,826
Piraeus	448,997
East Attica	502,348
West Attica	160,927
Total	3,752,973

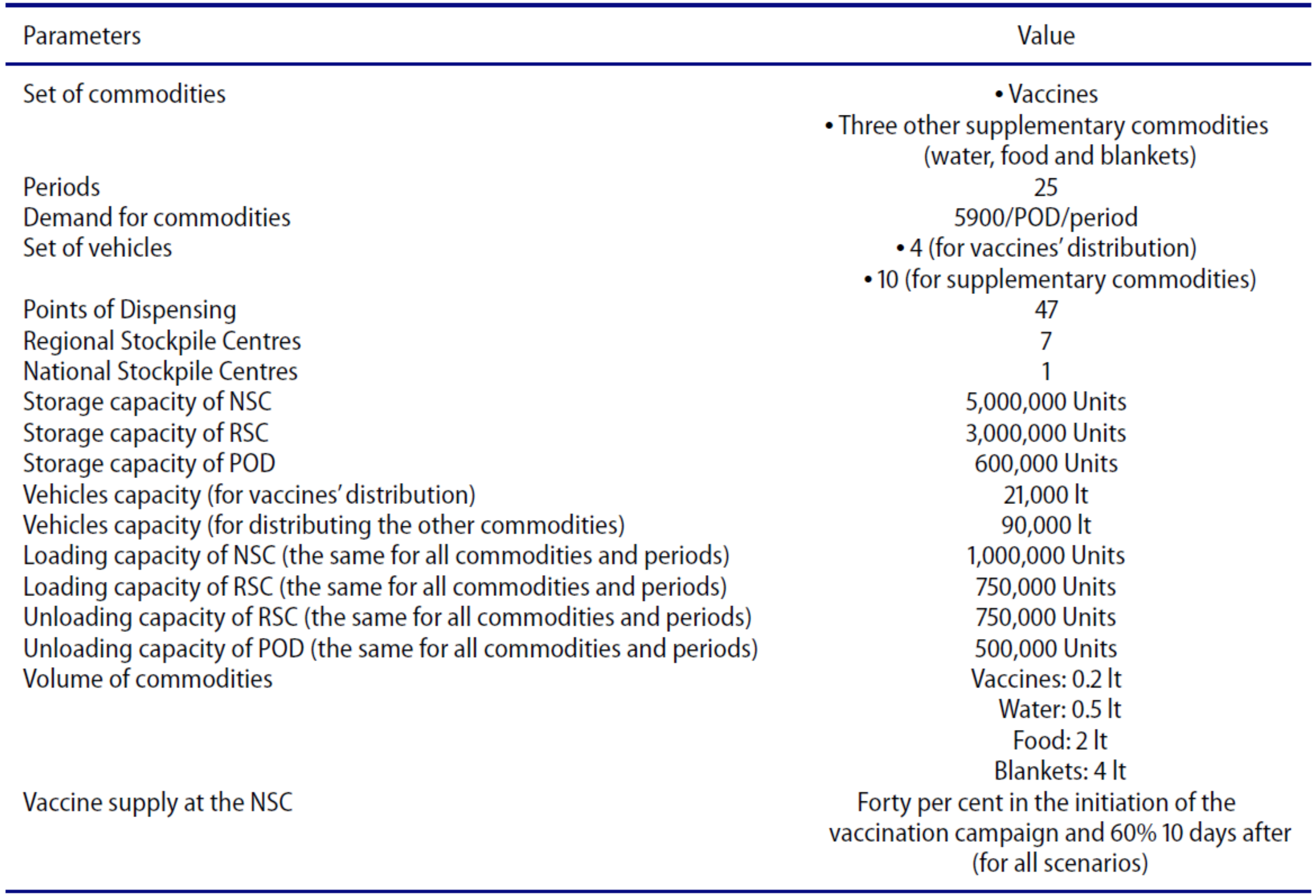


Number of VS	8 per VC
Number of vaccinators	1 per VS
Vaccination rate	30–60 vaccinations per VS/hour
Hours of operation for VC	24 hours/16 hours
Estimated overall vaccination rate per day/POD	8640/5900



Intervention policy	Scenario	Resource allocation policy
Case isolation	Baseline	–
Reactive regional mass vaccination within 4 days starting at days 22, 29, 36, 43 and 50 from the onset of the outbreak.	A_1	Unconstrained
	A_2	
	A_3	
	A_4	
	A_5	
Reactive regional mass vaccination within 9 days starting at days 22, 29, 36, 43 and 50 from the onset of the outbreak.	B_1	
	B_2	
	B_3	
	B_4	
	B_5	
Reactive regional mass vaccination starting at days 22, 29, 36, 43 and 50 from the onset of the outbreak with limited vaccine supply.	C_1	Constrained
	C_2	
	C_3	
	C_4	
	C_5	
Reactive regional mass vaccination starting at days 22, 29, 36, 43 and 50 from the onset of the outbreak where limited transportation capacity as well as limited vaccine supply are considered.	D_1	
	D_2	
	D_3	
	D_4	
	D_5	

Numerical experiments: Athens



Parameters	Value
Set of commodities	• Vaccines • Three other supplementary commodities (water, food and blankets)
Periods	25
Demand for commodities	5900/POD/period
Set of vehicles	• 4 (for vaccines' distribution) • 10 (for supplementary commodities)
Points of Dispensing	47
Regional Stockpile Centres	7
National Stockpile Centres	1
Storage capacity of NSC	5,000,000 Units
Storage capacity of RSC	3,000,000 Units
Storage capacity of POD	600,000 Units
Vehicles capacity (for vaccines' distribution)	21,000 lt
Vehicles capacity (for distributing the other commodities)	90,000 lt
Loading capacity of NSC (the same for all commodities and periods)	1,000,000 Units
Loading capacity of RSC (the same for all commodities and periods)	750,000 Units
Unloading capacity of RSC (the same for all commodities and periods)	750,000 Units
Unloading capacity of POD (the same for all commodities and periods)	500,000 Units
Volume of commodities	Vaccines: 0.2 lt Water: 0.5 lt Food: 2 lt Blankets: 4 lt
Vaccine supply at the NSC	Forty per cent in the initiation of the vaccination campaign and 60% 10 days after (for all scenarios)

Results

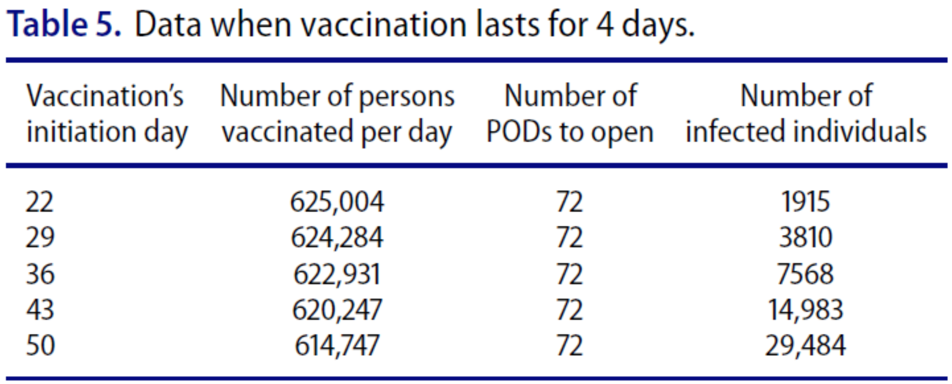


Table 5. Data when vaccination lasts for 4 days.

Vaccination's initiation day	Number of persons vaccinated per day	Number of PODs to open	Number of infected individuals
22	625,004	72	1915
29	624,284	72	3810
36	622,931	72	7568
43	620,247	72	14,983
50	614,747	72	29,484

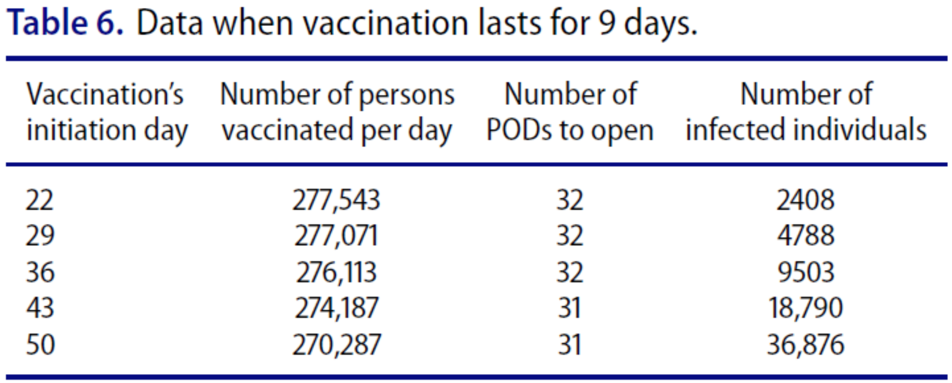


Table 6. Data when vaccination lasts for 9 days.

Vaccination's initiation day	Number of persons vaccinated per day	Number of PODs to open	Number of infected individuals
22	277,543	32	2408
29	277,071	32	4788
36	276,113	32	9503
43	274,187	31	18,790
50	270,287	31	36,876

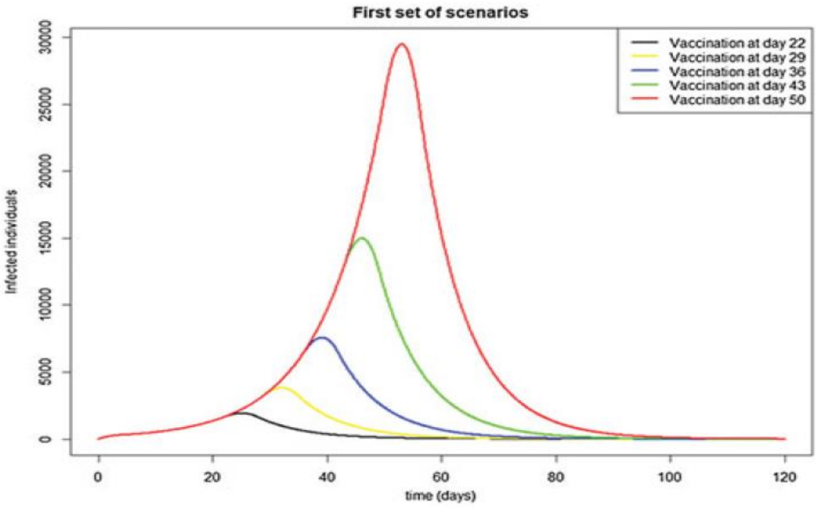


Figure 3. Number of infected individuals for the first set of scenarios.

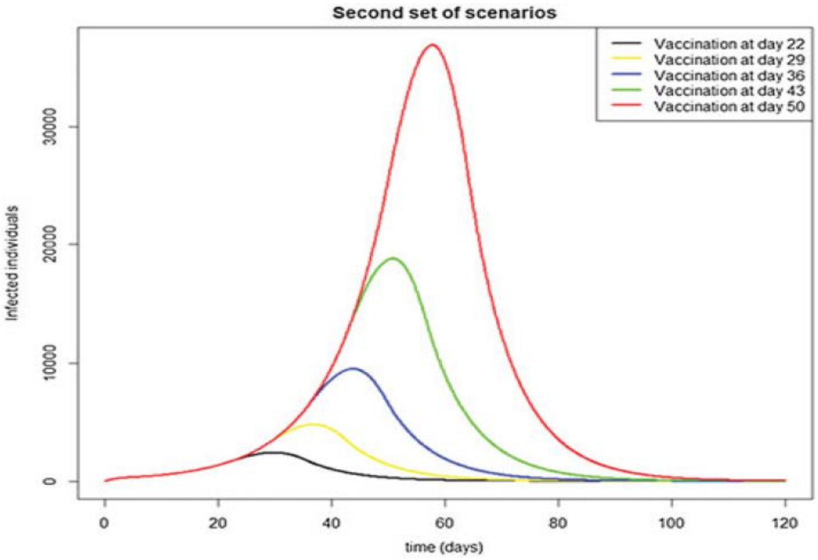


Figure 4. Number of infected individuals for the second set of scenarios.

Results

Regional units	Population	PODs required
Central Athens	1,029,520	13
North Athens	591,680	7
West Athens	489,675	6
South Athens	529,826	7
Piraeus	448,997	6
East Attica	502,348	6
West Attica	160,927	2
Total		47

Table 9. Results of the third set of scenarios.

Vaccination's initiation day	Vaccination's termination day	Day when effective reproduction number drops below 1	Infected individuals
22	39	35	2833
29	46	42	5623
36	53	49	11,119
43	60	56	21,826
50	67	62	42,238

Table 10. Results of the fourth set of scenarios.

Vaccination's initiation day	Vaccination's termination day	Day when effective reproduction number drops below 1	Infected individuals
22	43	38	3325
29	50	45	6,592
36	57	52	13,006
43	64	59	25,422
50	71	63	39,091

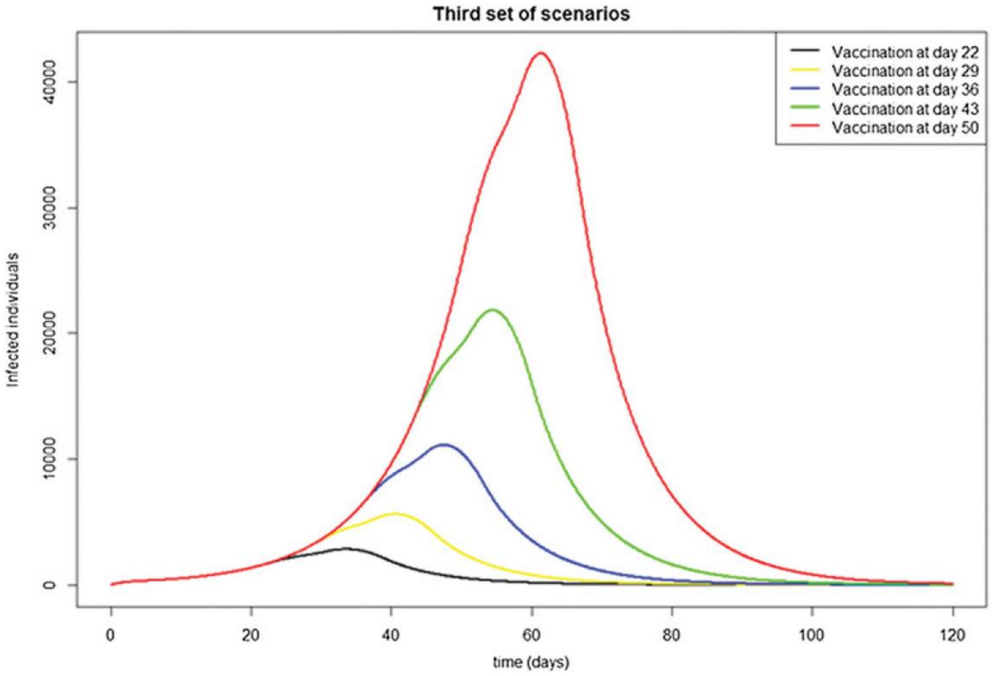


Figure 7. Number of infected individuals for the third set of scenarios.

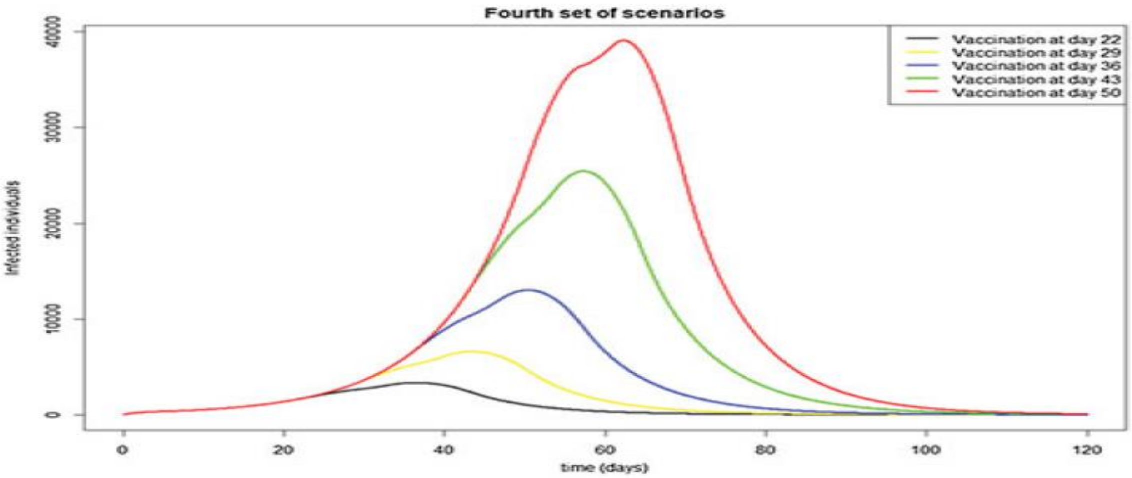


Figure 8. Number of infected individuals for the fourth set of scenarios.

Results

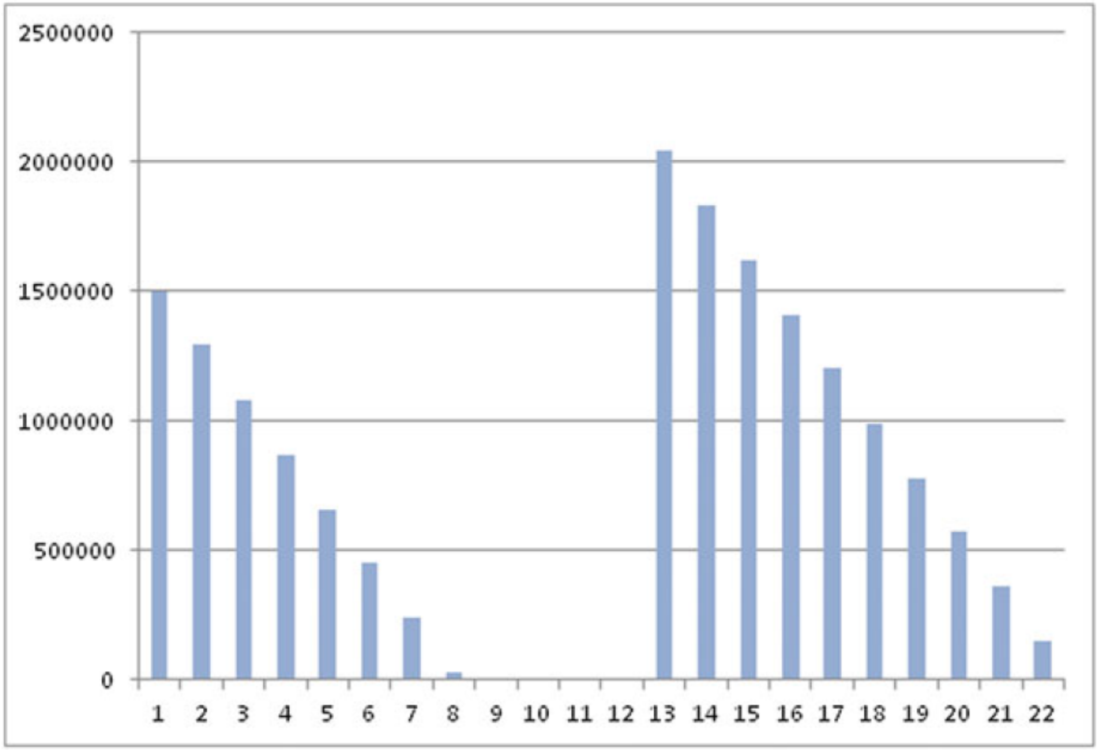


Figure 9. Vaccine's stockpile in the National Stockpile Centre for the fourth set of scenarios (per day).

Discussion

- Epidemics control supply chain literature is fragmented
- Most of the available frameworks have little correlation with real-case scenarios and, therefore, the applicability of the modeling approaches might be limited
- Several aspects of the nature of the outbreak or of the agent triggering the outbreak have not explicitly taken into consideration when relevant supply chain decisions are to be made.

Research directions

- Multidisciplinary synergies
- End-to-End approaches
- Evaluation of models and large scale exercises (applicability of existing modeling approaches)
- Performance metrics
- Cross-functional drivers
- Coordination issues.

Literature

1. T.K. Dasaklis, C.P. Pappis, N.P. Rachaniotis (2012). Epidemics control and logistics operations: A review. *International Journal of Production Economics*, **139, 2**: 398-410.

2. T.K. Dasaklis, N. Rachaniotis & Costas Pappis (2017). Emergency supply chain management for controlling a smallpox outbreak: the case for regional mass vaccination. *International Journal of Systems Science: Operations & Logistics*, **4, 1**: 27-40.

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