An ABM generating realistic epidemic dynamics and a genetic algorithm to implement vaccinations minimizing the number of symptomatic people

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Introduction

- A micro-based model of interacting agents, following plausible behavioral rules into a world where the Covid-19 epidemic is affecting the actions of everyone.
- The model works with:
  - i infected agents categorized as symptomatic or asymptomatic and
  - ii the places of contagion specified in a detailed way, thanks to agent-based modeling capabilities.
- The infection transmission is related to three factors: the infected person's characteristics and those of the susceptible one, plus those of the space in which a contact occurs.

- The micro-based structure of the model allows factual, counterfactual, and conditional simulations to investigate both the spontaneous or controlled development of the epidemic. Examples of counterfactual situations are those considering:
  - i different timing in the adoption of the non-pharmaceutical containment measures;
  - ii alternative strategies focusing exclusively on the defense of fragile people.
- The model generates complex epidemic dynamics, emerging from the consequences of agents' actions and interactions, with high variability in outcomes, but frequently with a stunning realistic reproduction of the contagion waves that occurred in the reference region.
- We take charge of the variability of the epidemic paths within the simulation, running batches of executions with 10,000 occurrences for each experiment.

- The AI and inverse generative sides of the model come from constructing a meta-agent optimizing the vaccine distribution among people groups—characterized by age, fragility, work conditions—to minimize the number of symptomatic people (deceased persons come from there).
- We can characterize the action of the planner both:
  - i introducing ex-ante rules following "plain" or "wise" strategies that we imagine as observers or
  - ii evolving those strategies via the application of a genetic algorithm.
- The genome is a matrix of vaccination quotas by people groups, with their time range of adoption.

The model

- As the agents can be Susceptible, Infected, symptomatic, asymptomatic, and Recovered, the name of the model is S.I.s.a.R., with the capital letters recalling the S.I.R. scheme.
- We use NetLogo, at `https://ccl.northwestern.edu/netlogo/`.
- S.I.s.a.R. is at `https://terna.to.it/simul/SIsaR.html` with information on model construction, and an online executable version.
- A short paper is published at `https://rofasss.org/2020/10/20/sisar/`
- The model includes the structural data of Piedmont, an Italian region, but we can easily calibrate it for other areas. The simulation reproduces a realistic calendar (e.g., national or local government decisions) via a dedicated script interpreter.

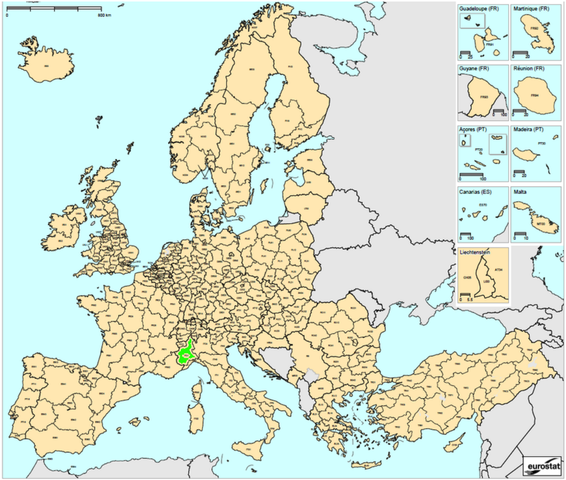


Figure 1: Piedmont

The scale and the items

- 1 : 1000, for a population of 4,350,000 people.

- Houses.
- Schools.
- Hospitals.
- Nursing homes,
- Factories.

The world 3D

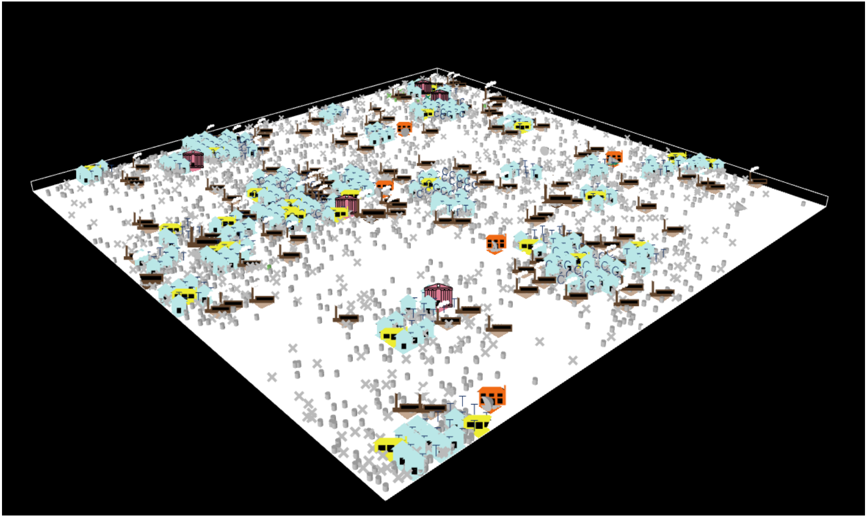


Figure 2: The world 3D

A circular scheme

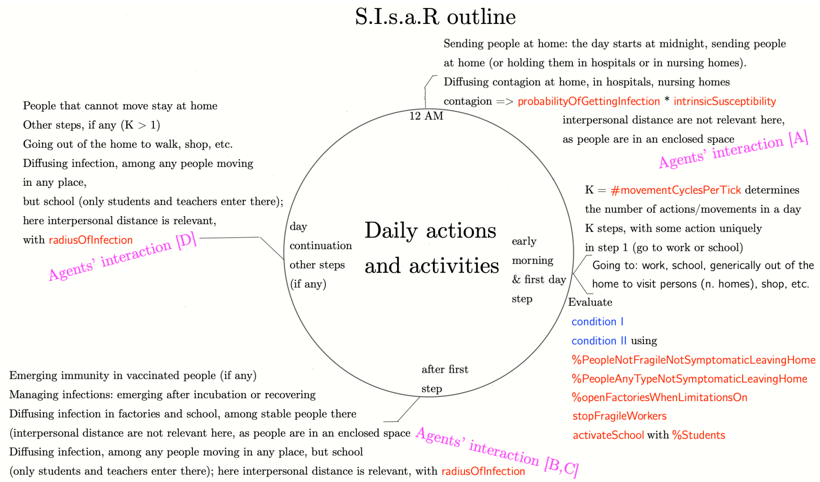


Figure 3: The scheme: def. and values of the parameters at `https://terna.to.it/simul/howSIsaRworks.pdf`

Contagion representation

- The model allows analyzing the sequences of contagions in simulated epidemics, reporting the places where the contagion occur.
- We represent each infected agent as a horizontal segment (from the starting date to the final date of the infection) with vertical connections to other agents if they receive the disease.
  We represent the new infected agents via further segments at an upper level.
- With colors, line thickness, and styles, we display multiple information.
- This enables understanding at a glance how an epidemic episode is developing. In this way, it is easier to reason about countermeasures and, thus, to develop intervention policies.

Examples (1/2)

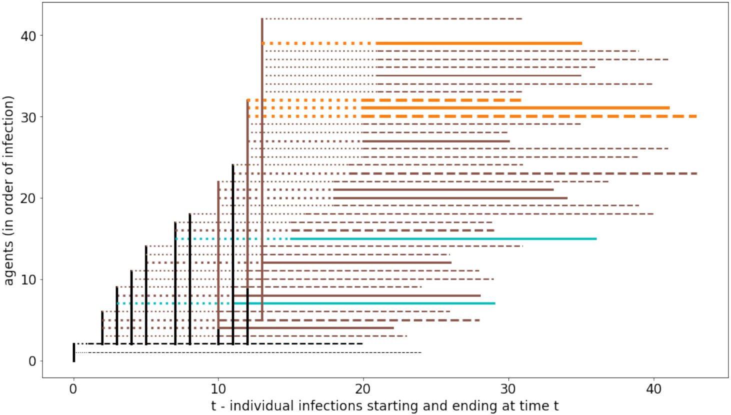


Figure 4: A case with containment measures, first 40 infections: workplaces (brown) and nursing homes (orange) strictly interweaving

Examples (2/2), whole epidemic

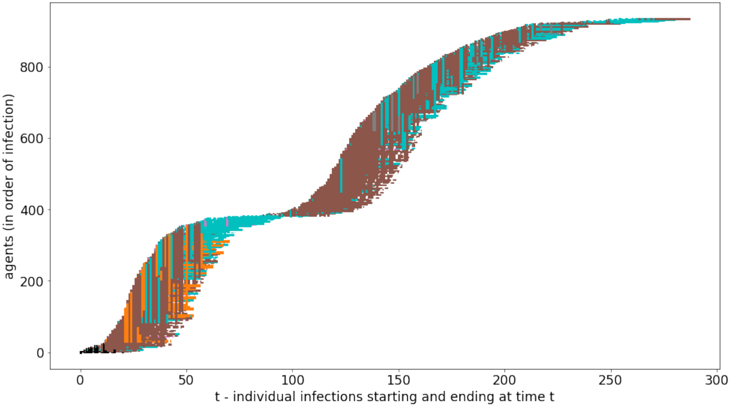


Figure 5: A Case with containment measures, the whole epidemics: workplaces (brown) and nursing homes (orange) and then houses (cyan), with a bridge connecting two waves

Simulation batches

- We explore systematically the introduction of factual, counterfactual, and prospective interventions to control the spread of the contagions.
- Each simulation run—whose length corresponds to the disappearance of symptomatic or asymptomatic contagion cases—is a datum in a wide scenario of variability in time and effects.
- We need to represent compactly the results emerging from batches of simulation repetitions, to compare the consequences of the basic assumptions adopted for each specific batch.
- Besides summarizing the results with the usual statistical indicators, we adopt the technique of the heat-maps.
- Each heat-map reports the duration of each simulated epidemic in the x axis and the number of the symptomatic, asymptomatic, and deceased agents in the y axis. The z axis is represented by the colors, as in the logarithmic scale on the right of each picture.
- In our batches we have 10,000 runs.

10,000 epidemics without control in Piedmont

	symptomatic	totalInfected&Deceased	duration
count	10000.00	10000.00	10000.00
mean	969.46	2500.45	303.10
std	308.80	802.88	93.50

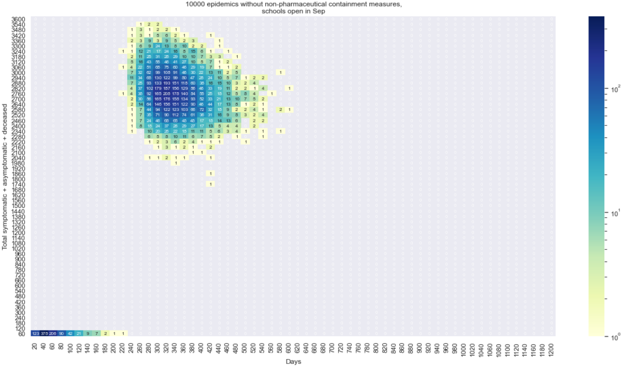


Figure 6: Without non-pharmaceutical containment measures

10,000 epidemic with basic control in Piedmont

	symptomatic	totalInfected&Deceased	duration
count	10000.00	10000.00	10000.00
mean	344.22	851.64	277.93
std	368.49	916.41	213.48

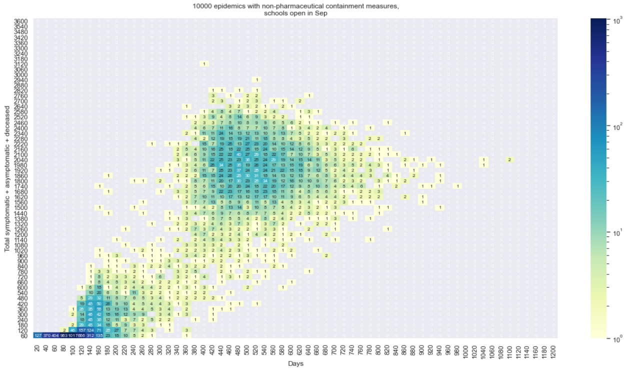


Figure 7: First wave with non-pharmaceutical containment measures

Key points (Summer and Fall 2020)

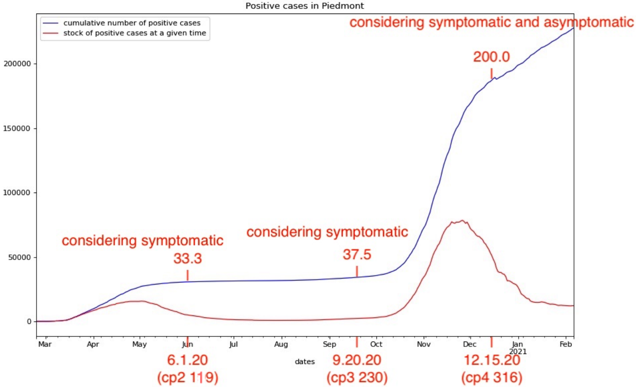


Figure 8: key points in epidemic dynamic in Summe and Fall 2020

Non homogeneous data

- Following the Civil Protection Department web site `http://www.protezionecivile.it/web/guest/department`, we find the repository `https://github.com/pcm-dpc/COVID-19`.
- In the first wave we had uniquely data about symptomatic infected people, but from October 2020 data are mixed.
- In the above *git* repository, in October and November we had "Positive cases emerged from clinical activity", unfortunately then reported as "No longer populated" (from the end of November, my observation) and "Positive cases emerging from surveys and tests, planned at national or regional level", again "No longer populated" (from the end of November, my observation).
- Using those two series, it was possible to estimate a subdivision between symptomatic and asymptomatic cases, which is no longer possible.

Updated series, with a third wave (data until the beginning of June)

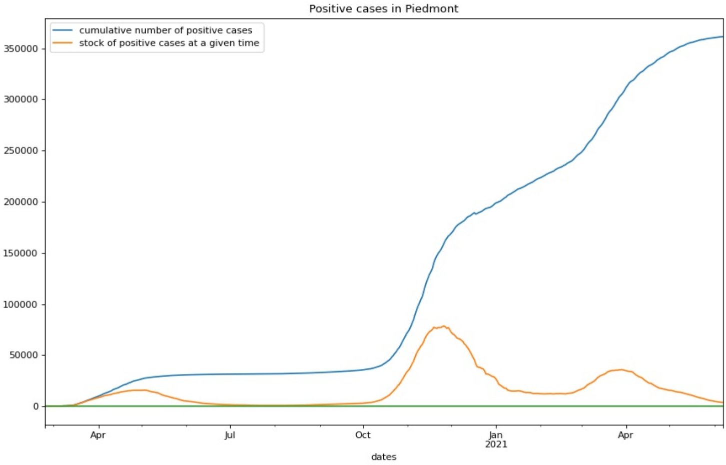


Figure 9: Data for Piedmont

Spontaneous second wave, without specific measures

170 epidemics stable in Summer 2020 out of 10,000, rule: at Jun 1, 20 select if sym. (10, 70], actual v. 33.3 & at Sep 20, 20 select if sym. (20, 90], actual value 37.5; **140** at Dec 15, 20, rule: sym.+asym.>Sep 20, 20, actual value: 200.0.

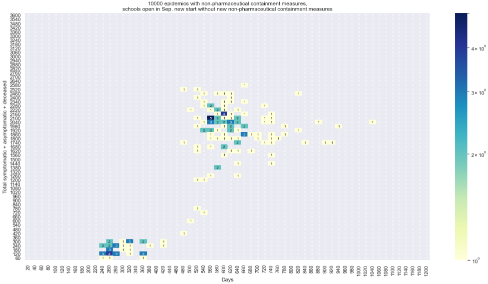


Figure 10: First wave with non-pharmaceutical containment measures, spontaneous second wave, without specific measures

(1000) cum. v.	Jun 1, 20 sym.	all	Sep 9, 20 sympt.	totalInf.	Dec 15, 20 sympt.	totalInf.	Feb 1, 21 sympt.	totalInf.	May 1, 21 sympt.	totalInf.	Dec 15, 20 to end sympt.	totalInf.	days
count	170.0	170.0	170.0	170.0	140.0	140.0	131.0	131.0	128.0	128.0	140.0	140.0	140.0
mean	37.9	100.2	60.4	159.3	**248.4**	**648.7**	**432.2**	**1109.5**	**656.3**	**1655.5**	701.1	1757.9	594.2
std	16.4	61.0	19.6	71.7	167.4	424.3	220.4	538.4	215.4	513.3	246.4	599.7	118.9

Second w., new infections from outside, without specific measures

1407 epidemics stable in Summer 2020 out of 10,000, rule: at Jun 1, 20 select if sym. (10, 70], actual v. 33.3 & at Sep 20, 20 select if sym. (20, 90], actual value 37.5; **1044** at Dec 15, 20, rule: sym.+asym.>Sep 20, 20, actual value: 200.0.

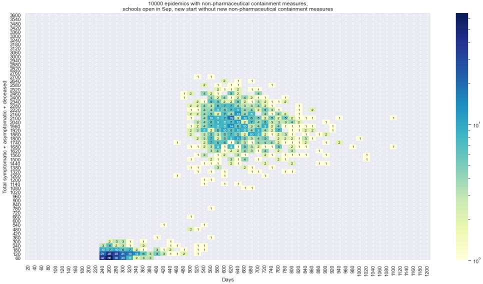


Figure 11: First wave with non-pharmaceutical containment measures, forcing the second wave, without specific measures

(1000)	Jun 1, 20		Sep 9, 20		Dec 15, 20		Feb 1, 21		May 1, 21		Dec 15, 20 to end		
cum. v.	sym.	all	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	days
count	1407.0	1407.0	1407.0	1407.0	1044.0	1044.0	1005.0	1005.0	980.0	980.0	1044.0	1044.0	1044.0
mean	35.6	72.7	40.0	84.1	**180.4**	**462.1**	**354.1**	**900.4**	**623.8**	**1563.3**	726.6	1810.9	620.9
std	14.1	42.6	16.7	52.8	134.6	354.6	213.8	535.4	217.9	527.0	221.9	544.0	110.8

Second w., new infections from outside, with new specific measures

1407 epidemics stable in Summer 2020 out of 10,000, rule: at Jun 1, 20 select if sym. (10, 70], actual v. 33.3 & at Sep 20, 20 select if sym. (20, 90], actual value 37.5; **874** at Dec 15, 20, rule: sym.+asym.>Sep 20, 20, actual value: 200.0.

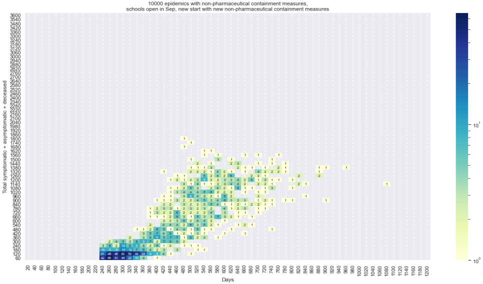


Figure 12: First wave with non-ph. containment measures, forcing the second wave, **with new specific non-ph. containment measures**

(1000) cum. v.	Jun 1, 20 sym.	all	Sep 9, 20 sympt.	totalInf.	Dec 15, 20 sympt.	totalInf.	Feb 1, 21 sympt.	totalInf.	May 1, 21 sympt.	totalInf.	Dec 15, 20 to end sympt.	totalInf.	days
count	1407.0	1407.0	1407.0	1407.0	874.0	874.0	719.0	719.0	523.0	523.0	874.0	874.0	874.0
mean	35.6	72.7	40.0	84.1	**130.0**	**340**.6	**194.4**	**512.8**	**295.7**	**791.2**	252.7	666.4	494.1
std	14.1	42.6	16.7	52.8	83.9	232.6	104.1	276.9	119.1	300.6	156.8	416.4	122.7

Time factor

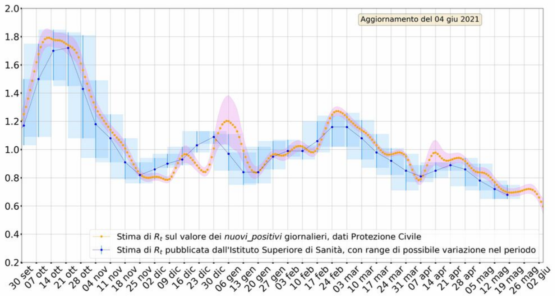


Figure 13: In blue the R_t values as reported by the Istituto Superiore di Sanità and in red the calculation published regularly at https://mondoeconomico.eu by Stefano Terna[1].

[1] Methodology: https://github.com/tomorrowdata/COVID-19/blob/main/notebooks/Rt_on_italian_national_data.ipynb

Second w., new infect. from outside, with new specific meas. -20 days[2]

1407 epidemics stable in Summer 2020 out of 10,000, rule: at Jun 1, 20 select if sym. (10, 70], actual v. 33.3 & at Sep 20, 20 select if sym. (20, 90], actual value 37.5; **769** at Dec 15, 20, rule: sym.+asym.>Sep 20, 20, actual value: 200.0.

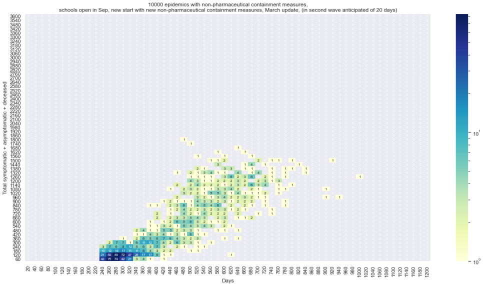


Figure 14: First wave with non-ph. cont. meas., forcing the second wave, **with new specific non-ph. cont. meas., 20 day anticipation**

(1000)	Jun 1, 20		Sep 9, 20		Dec 15, 20		Feb 1, 21		May 1, 21		Dec 15, 20 to end		
cum. v.	sym.	all	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	days
count	1407.0	1407.0	1407.0	1407.0	769.0	769.0	637.0	637.0	471.0	471.0	769.0	769.0	769.0
mean	35.6	72.7	40.0	84.1	**112.2**	**294.2**	**172.0**	**467.9**	**276.5**	**748.6**	248.9	663.4	499.3
std	14.1	42.6	16.7	52.8	66.8	188.4	91.5	251.3	112.9	286.9	158.0	417.5	124.1

[2] N.B.: (i) anticipation limit Oct 5.; (ii) also the ending date of each measure is anticipated of 20 days.

Fragile persons

- A possible strategy is to stop all fragile people for a given period when R_t starts increasing (also with fragile workers in sick leave, if unable to work remotely).
- We have also relevant social benefits, e.g., schooling, and economic benefits, as activities do not stop

Sec. w., new infect. from outs., stop fragile people. 60 days from Oct. 5[3]

1407 epidemics stable in Summer 2020 out of 10,000, rule: at Jun 1, 20 select if sym. (10, 70], actual v. 33.3 & at Sep 20, 20 select if sym. (20, 90], actual value 37.5; **886** at Dec 15, 20, rule: sym.+asym.>Sep 20, 20, actual value: 200.0.

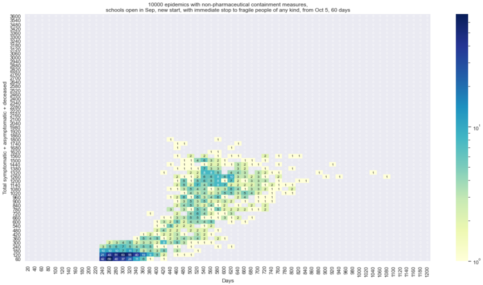


Figure 15: First wave with non-ph. cont. meas., forcing the sec. w.; **in sec. w., uniquely stop fragile people, including fragile workers**

(1000)	Jun 1, 20		Sep 9, 20		Dec 15, 20		Feb 1, 21		May 1, 21		Dec 15, 20 to end		
	sym.	all	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	sympt.	totalInf.	days
count	1407.0	1407.0	1407.0	1407.0	886.0	886.0	761.0	761.0	637.0	637.0	886.0	886.0	886.0
mean	35.6	72.7	40.0	84.1	**128.1**	**326.3**	**211.0**	**555.1**	**323.3**	**862.1**	301.1	792.3	515.5
std	14.1	42.6	16.7	52.8	89.6	234.2	118.1	306.7	126.4	315.9	170.7	450.2	116.9

[3] Schools are always working 100% in this case.

To recap (all waves)

Scenarios		Dec 15, 20 sympt.	Dec 15, 20 totalInf.	Dec 15, 20 to end sympt.	Dec 15, 20 to end totalInf.	Dec 15, 20 to end days
no containments in spontaneous second wave	count	140.0	140.0	140.0	140.0	140.0
	mean	**248.4**	**648.7**	701.1	1757.9	594.2
	std	167.4	424.3	246.4	599.7	118.9
no containments in forced second wave	count	1044.0	1044.0	1044.0	1044.0	1044.0
	mean	**180.4**	**462.1**	726.6	1810.9	620.9
	std	134.6	354.6	221.9	544.0	110.8
basic containements in forced second wave	count	874.0	874.0	874.0	874.0	874.0
	mean	**130.0**	**340**.6	252.7	666.4	494.1
	std	83.9	232.6	156.8	416.4	122.7
-20 days containments in forced second wave	count	769.0	769.0	769.0	769.0	769.0
	mean	**112.2**	**294.2**	248.9	663.4	499.3
	std	66.8	188.4	158.0	417.5	124.1
frag. p. & workers control in forced second wave	count	886.0	886.0	886.0	886.0	886.0
	mean	**128.1**	**326.3**	301.1	792.3	515.5
	std	89.6	234.2	170.7	450.2	116.9

Table 1: Report of the key results, with count, mean, and std

Planning a vaccination campaign using GAs (with non-pharmaceutical containment measures in action)

- Exploring vaccination sequences, using *genetic algorithms*. A detailed note, frequently updated, is at `https://terna.to.it/simul/GAresultPresentation.pdf`.
- We compare the effect of choosing the vaccination quotas via GAs with two predetermined strategies, considering three hypotheses (vaccinated people: still spread the contagion; do not spread the contagion; do it in the 50% of the case); we show here only the first case results.
- Key dates:
  - in the internal calendar of the model, day 373 is Feb. 12th, 2021, which is effectively the starting point of the vaccinations in the region;
  - the day of the effectiveness of the initial vaccinations, 40 days later, is day 413 (Mar. 22nd, 2021).

Vaccination groups

We take into consideration seven groups in order of decreasing fragility but also considering the exposure to contagion:

g1 extra fragile people with three components;
- due to intrinsic characteristics: people in nursing homes;
- due to risk exposure:
  - nursing homes operators;
  - healthcare operators;

g2 teachers;

g3 workers with medical fragility;

g4 regular workers;

g5 fragile people without special characteristics;

g6 regular people, not young, not worker, and not teacher;

g7 young people excluding special activity cases (a limited number in *g1*).

A specific realistic case

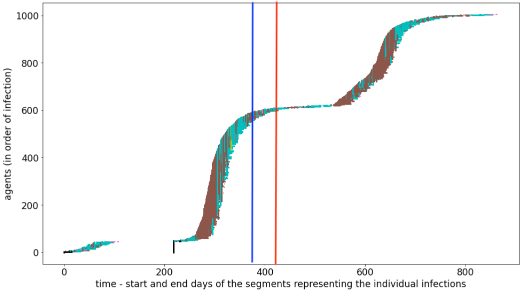


Figure 16: Crucial dates: blue line for the starting point of the vaccination campaign and red line for the start of the effectiveness of the initial vaccinations

Vaccination quotas, *plain* strategy

Considering the *plain* option adopted in Table 2 and remembering that the time-sequence in daily actions is the priority, we will primarily vaccinate the left column groups to move gradually to other columns: (*g1*) extra fragile people, (*g2*) teachers, (*g3*) fragile workers, (*g4*) regular workers, (*g5*) fragile people, (*g6*) regular people, (*g7*) young people.

From day	Q. of vaccines (000)	*g1*	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*
373	5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
433	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
493	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
553	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
613	20	0.1	0.1	0.1	0.1	0.1	0.1	0.1
738	end							

Table 2: From the day of the first column, considering the quantity of the second column (000), the vaccination of each group follows the quota of the related columns

(000)	*g1*	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*
Susc. at t = 0	133	84	240	1560	1179	254	900

Table 3: Susceptible persons at the beginning of the simulation

Vaccination quotas, *wise* strategy

Considering the *wise* option adopted in Table 4 and remembering that the time-sequence in daily actions is the priority, we will primarily vaccinate the left column groups to move gradually to other columns, but postponing group *g4* (regular workers), *g6* (regular people), and *g7* (young people).

From day	Q. of vaccines (000)	*g1*	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*
373	5	0.1	0.1	0.1	0.0	0.1	0.0	0.0
433	10	0.1	0.1	0.1	0.0	0.1	0.0	0.0
493	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
553	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
613	20	0.1	0.1	0.1	0.1	0.1	0.1	0.1
738	end							

Table 4: From the days of the first column, considering the quantity of the second column (000), the vaccination of each group follows the quota of the related columns

(000)	*g1*	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*
Susc. at t = 0	133	84	240	1560	1179	254	900

Table 5: Susceptible persons at the beginning of the simulation

GAs quotas in the experiment, with vac. people still spreading the infection

	g1	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*
Susc. at t = 0	133	84	240	1560	1179	254	900
Susc. when vacc. starts	124	81	162	1234	1032	245	891

Table 6: Susceptible persons at the beginning of the simulation and when the vaccination campaign starts, day 373, Feb. 12th, 2021

Groups: (*g1*) extra fragile people, (*g2*) teachers, (*g3*) fragile workers, (*g4*) regular workers, (*g5*) fragile people, (*g6*) regular people, (*g7*) young people.

From day	Q. of vaccines (000)	*g1*	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*
373	5	0.01	0	0	0.79	0.18	0.38	0.19
433	10	0.94	0.06	0.32	0.54	0.19	0.83	0.5
493	10	0.97	0.97	0.74	0.79	0.2	0.14	0.52
553	10	0.98	0.83	0.02	0.39	0.99	0.04	0.48
613	20	0.52	0.01	0.83	0.6	1	0.27	0.9
738	end							

Table 7: GAs best strategy in case I, with ***vaccinated people still spreading the infection***: from the day of the first column, considering the quantity of the second column, the vaccination of each group follows the quota of the related columns

Time dynamics without vaccinations

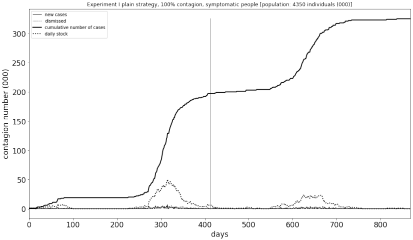


Figure 17: Experiment I, 'base symptomatic series; the vertical line is at day 413 is not relevant here

Time dynamics with *plain* vac. strategy, vac. people still spreading the infection

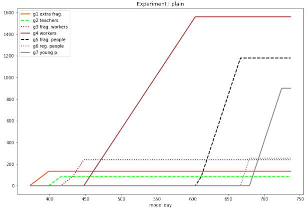


Figure 18: “Plain” vaccination sequence; on the y axis the number of vaccinated subjects of each group (if vaccination is complete, the line is horizontal)

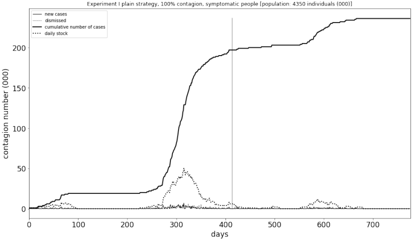


Figure 19: “Plain” vaccination symptomatic series; the vertical line is at day 413, when the effectiveness of first vaccination starts

Time dynamics with *wise* vac. strategy, vac. people still spreading the infection

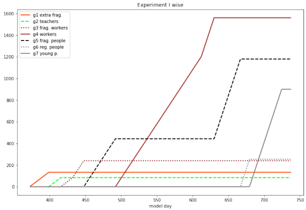


Figure 20: “Wise” vaccination sequence; on the y axis the number of vaccinated subjects of each group (if vaccination is complete, the line is horizontal)

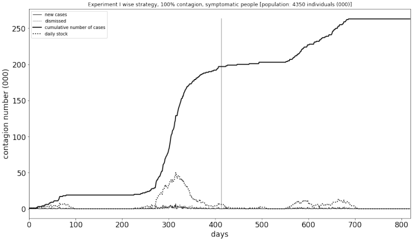


Figure 21: “Wise” vaccination symptomatic series; the vertical line is at day 413, when the effectiveness of first vaccination starts

Time dynamics with best GAs strategy, vac, people still spreading the infection

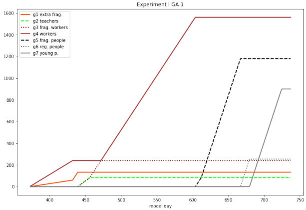


Figure 22: GA 1 vaccination sequence; on the *y* axis the number of vaccinated subjects of each group (if vaccination is complete, the line is horizontal)

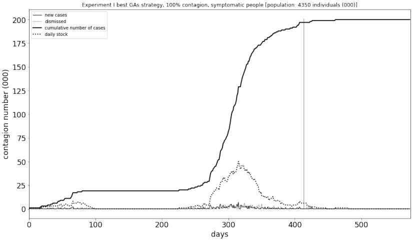


Figure 23: GAs vaccination symptomatic series; the vertical line is at day 413, when the effectiveness of first vaccination starts

What if

What if we increase quantities in *plain* and *wise* strategies?

From day	Q.	Q. +
373	5	10
433	10	15
493	10	25
553	10	25
613	20	25
738	end	

Table 8: New daily quantities

Time dynamics with *plain*+ vac. strategy, v. people still spreading the infection

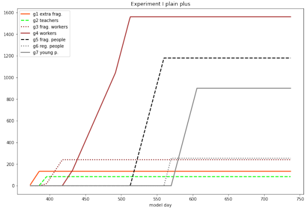


Figure 24: “Plain+” vaccination sequence; on the y axis the number of vaccinated subjects of each group (if vaccination is complete, the line is horizontal)

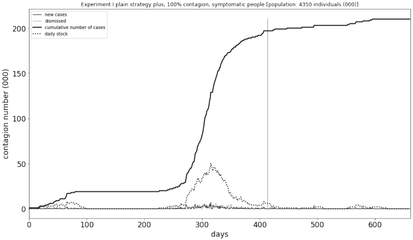


Figure 25: “Plain” vaccination symptomatic series; the vertical line is at day 413, when the effectiveness of first vaccination starts

Time dynamics with *wise+* vac. strategy, v. people still spreading the infection

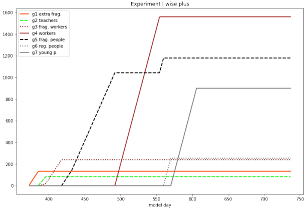


Figure 26: “Wise+” vaccination sequence; on the y axis the number of vaccinated subjects of each group (if vaccination is complete, the line is horizontal)

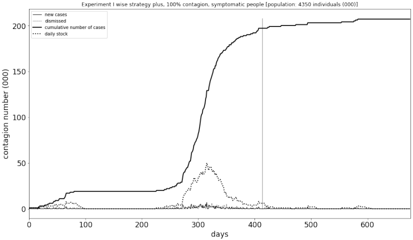


Figure 27: “Wise+” vaccination symptomatic series; the vertical line is at day 413, when the effectiveness of first vaccination starts

Synopsis

Hypothesis: vaccinated people, if infected, are diffusing the contagion.

Case (1000)	At day 413	Final no vaccin.	Final plain vaccin.	Final wise vaccin.	Final GAs vaccin.	Final plain + vaccin.	Final wise + vaccin.
I	197 -	325 128	236 39	263 66	**200** **3**	210 13	207 10

Table 9: Results of the vaccination campaigns: only symptomatic people (second row: minus day 413)

A new model: the map

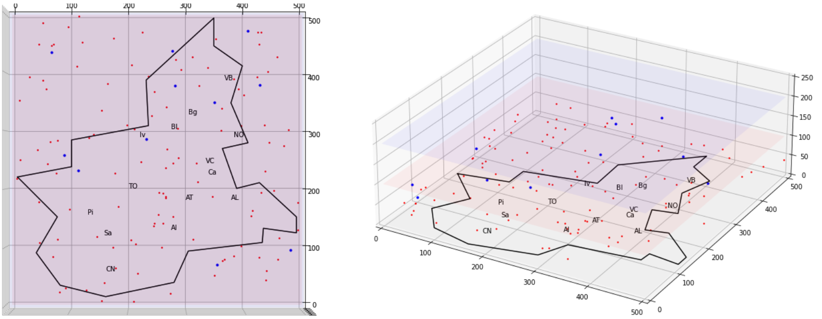


Figure 28: 3D Piedmont

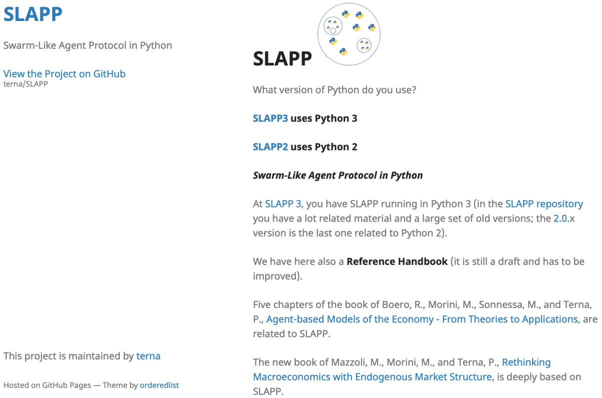
A new model: the scale and the items

- 1 : 100.
- *Infection engine*, https://terna.to.it/simul/InfectionEngine.pdf.
- Houses.
- Schools.
- Hospitals.
- Nursing homes,
- Factories.
- Transportations.
- Aggregation places: happy hours, night life, sport stadiums, discotheques, ...
- Networks (family networks, professional networks, high-contact individuals,[4] ...)

[4] G. Manzo and A. van de Rijt. Halting sars-cov-2 by targeting high-contact individuals. Journal of Artificial Societies and Social Simulation, 23(4):10, 2020. ISSN 1460-7425. doi: 10.18564/jasss.4435. URL http://jasss.soc.surrey.ac.uk/23/4/10.html.

The tool: S.L.A.P.P.

Scientific advertising: `https://terna.github.io/SLAPP/`



SLAPP

Swarm-Like Agent Protocol in Python

View the Project on GitHub
terna/SLAPP

This project is maintained by terna

Hosted on GitHub Pages — Theme by orderedlist

SLAPP

What version of Python do you use?

SLAPP3 uses Python 3

SLAPP2 uses Python 2

Swarm-Like Agent Protocol in Python

At SLAPP 3, you have SLAPP running in Python 3 (in the SLAPP repository you have a lot related material and a large set of old versions; the 2.0.x version is the last one related to Python 2).

We have here also a **Reference Handbook** (it is still a draft and has to be improved).

Five chapters of the book of Boero, R., Morini, M., Sonnessa, M., and Terna, P., Agent-based Models of the Economy - From Theories to Applications, are related to SLAPP.

The new book of Mazzoli, M., Morini, M., and Terna, P., Rethinking Macroeconomics with Endogenous Market Structure, is deeply based on SLAPP.

Figure 29: Swarm-Like Agent Protocol in Python

Some final considerations

- The importance of High Performance Computing.
- The S.I.s.a.R. model is a tool for comparative analyses, not for forecasting (the enormous standard deviation values are intrinsic to the problem).
- The model is highly parametric and more it will be.
- A small progress in the direction of using AI and inverse construction in agent-based models.

The slides are at
https://terna.to.it/simul/PietroTerna_iGSS20210608.pdf.
My homepage https://terna.to.it and my mail address
pietro.terna@unito.it.