Model M - an agent-based epidemiological model

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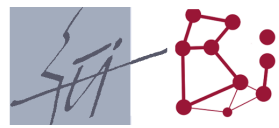
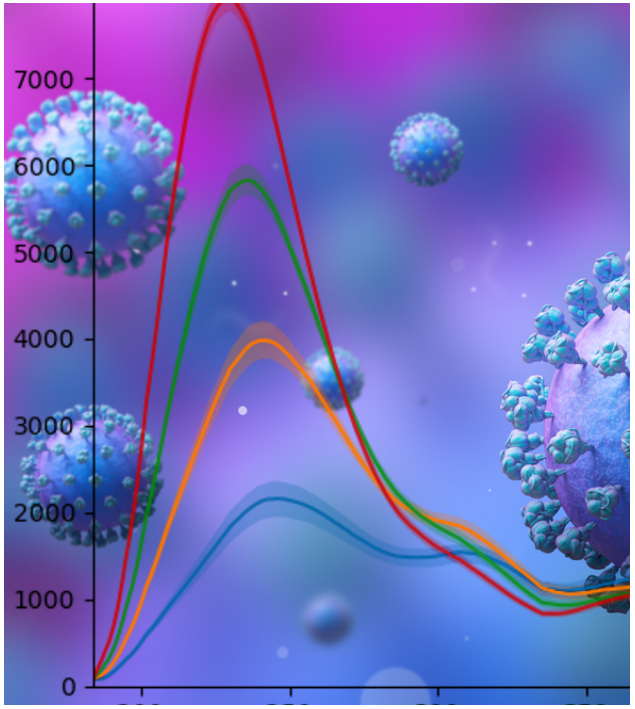
Hora Informaticae, December 6, 2022



Let's go back in time to 2020 and the start of the pandemic.

Contents



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- Vít Tuček, Zagreb Uni.
- Petra Vidnerová, ÚI AV ČR
- Karel Vrbenský, ÚTIA AV ČR
- Milan Zajíček, ÚTIA AV ČR
- and others

www.bisop.cz

Data from PAQ and MEDIAN.

Introduction

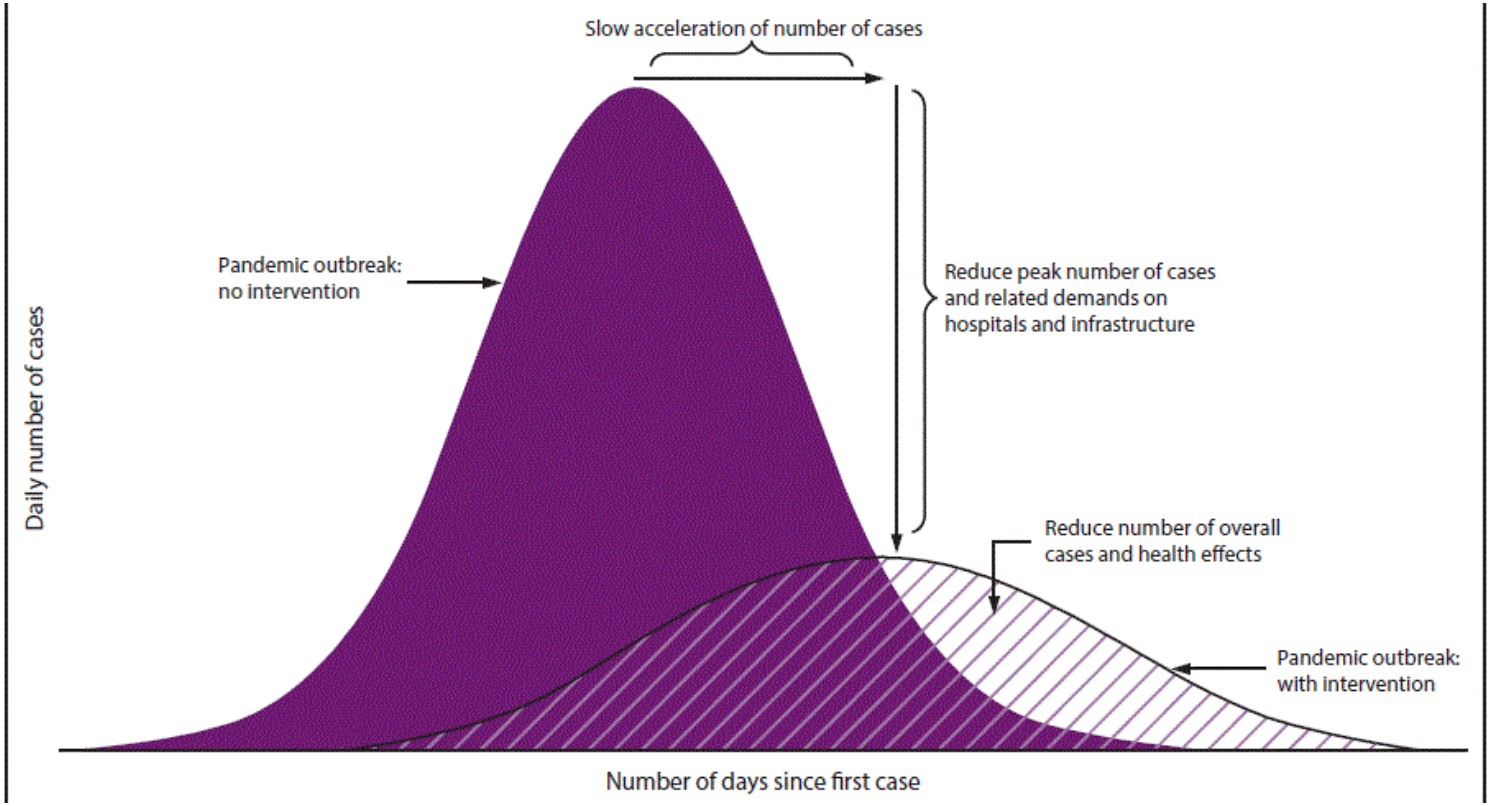
Why models?

- Understanding
- Prediction
- Study of interventions

Epidemic Modelling

- Modelling is an important tool in epidemic control
- Non-pharmaceutical interventions slow down the spread of a virus
- Models has to reflect the interventions valid at the moment

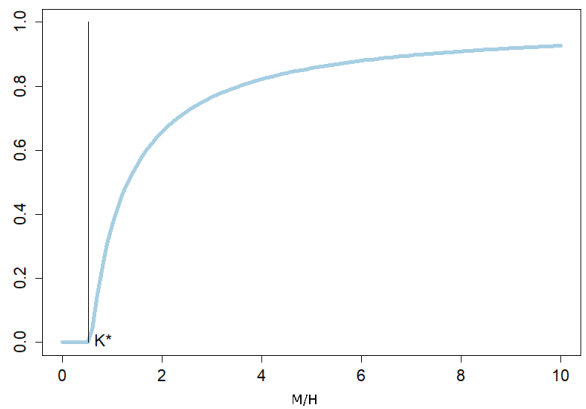
Epidemic curve



Epidemiological models

History

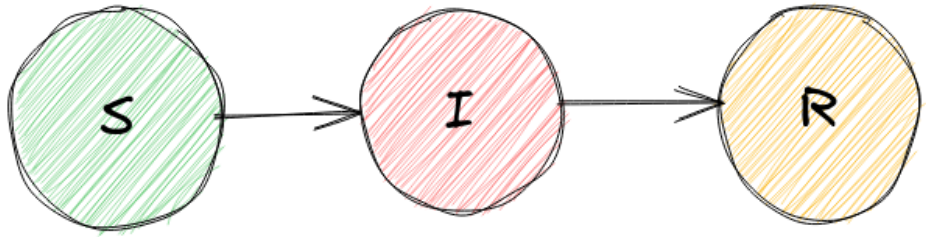
- 18th century - Daniel Bernoulli (1700–1782) - first mathematical approach to infectious disease, regarding variola
- Ronald Ross (1857–1932) - model of malaria



Model types

- compartment models - groups, susceptible, infected, recovered
- agent based models - work on individual level

SIR model (Kermack and McKendrick, 1927)

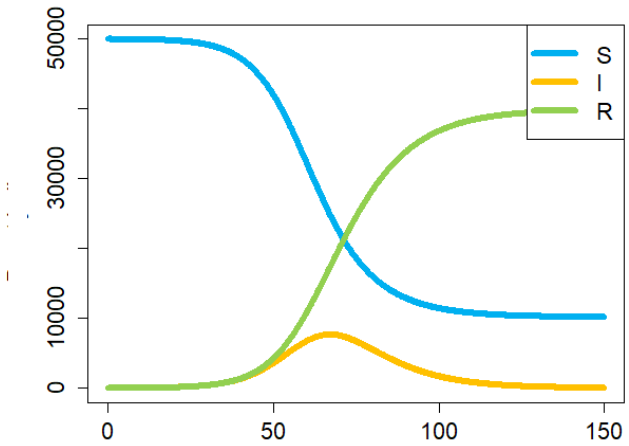


- $S(t)$ - susceptible
- $I(t)$ - infectious
- $R(t)$ - recovered/removed
- β infection rate, γ recovery rate

$$S[t+1] = S[t] - \beta \frac{S[t]\, I[t]}{N},$$

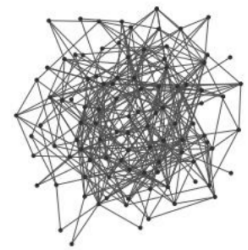
$$I[t+1] = I[t] + \beta \frac{S[t]\, I[t]}{N} - \gamma I[t],$$

$$R[t+1] = R[t] + \gamma I[t],$$



From Compartments to Agents

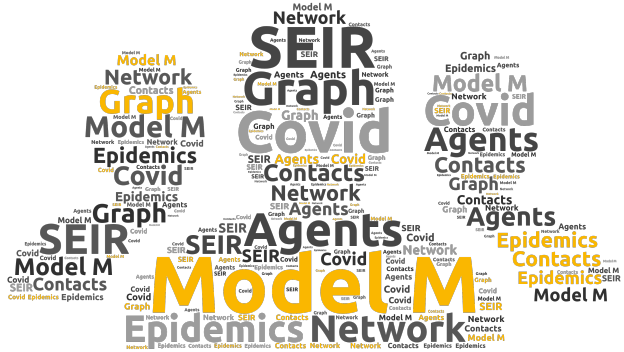
- Compartment models have difficulties in modelling non-pharamaceutical interventions (contact reductions, partial closures)



- Agent models work with a population of individuals
- Agents are connected in a network, i.e. a contact grapn

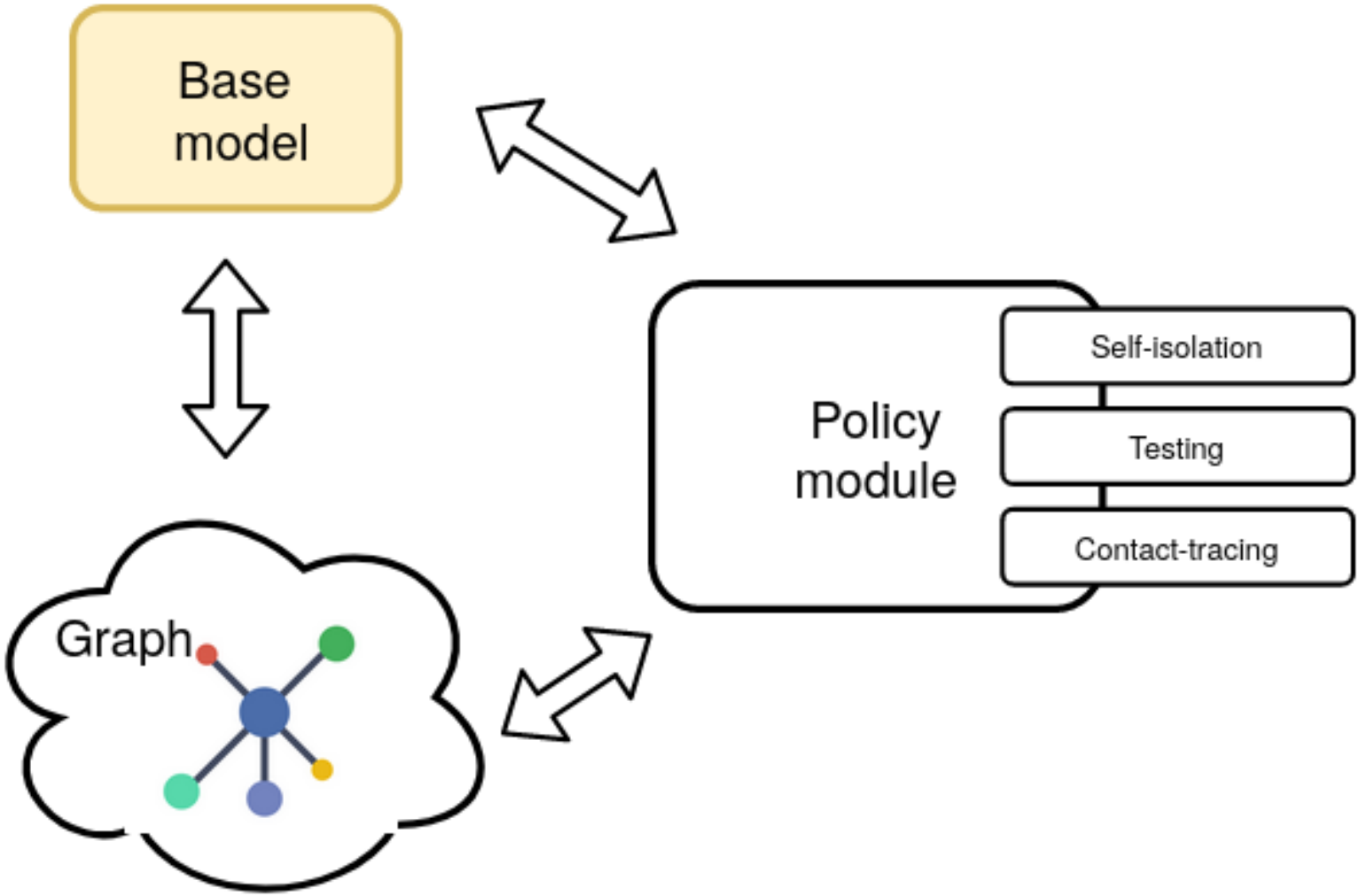
- Agents provide simulation tools for modelling of individual human behaviour
- Enable detailed simulation of various interventions

Model M



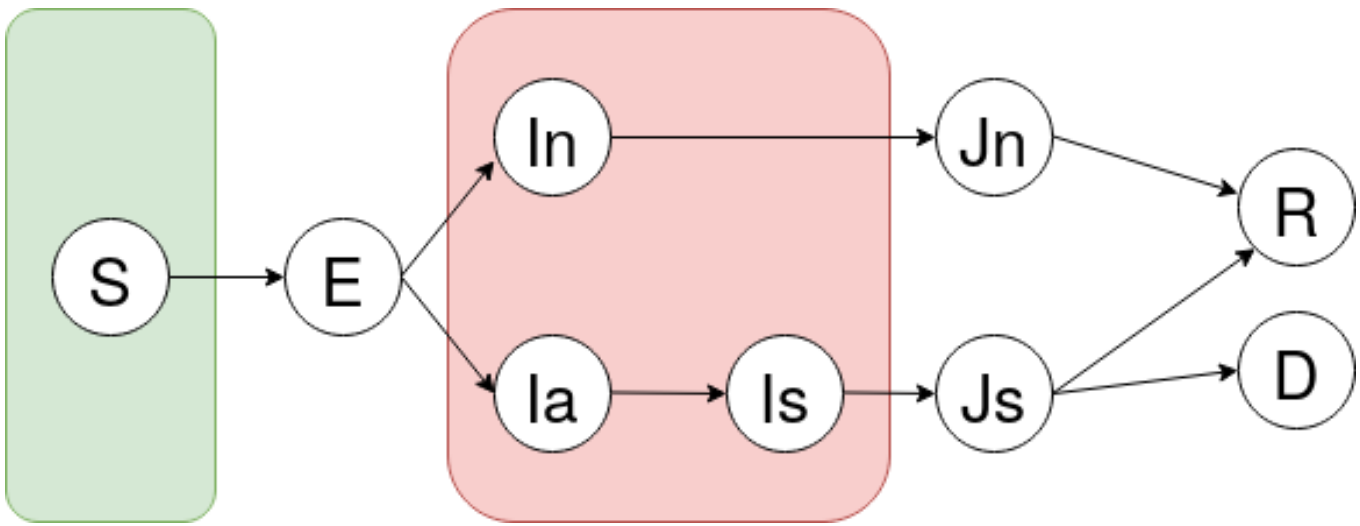
- Agent based model
- Why M? M referes to the world “town” (in Czech “město”)
- Works with a population of individuals (56 000 nodes/agents)
- Uses a realistic contact graph
- The graph models one Czech county
- Focus on comparing interventions (rather than on precise forecasting)
- Enables modelling of non-pharmaceutical interventions
- Simulates quarantines, isolations, flat closures on individual level

Model M

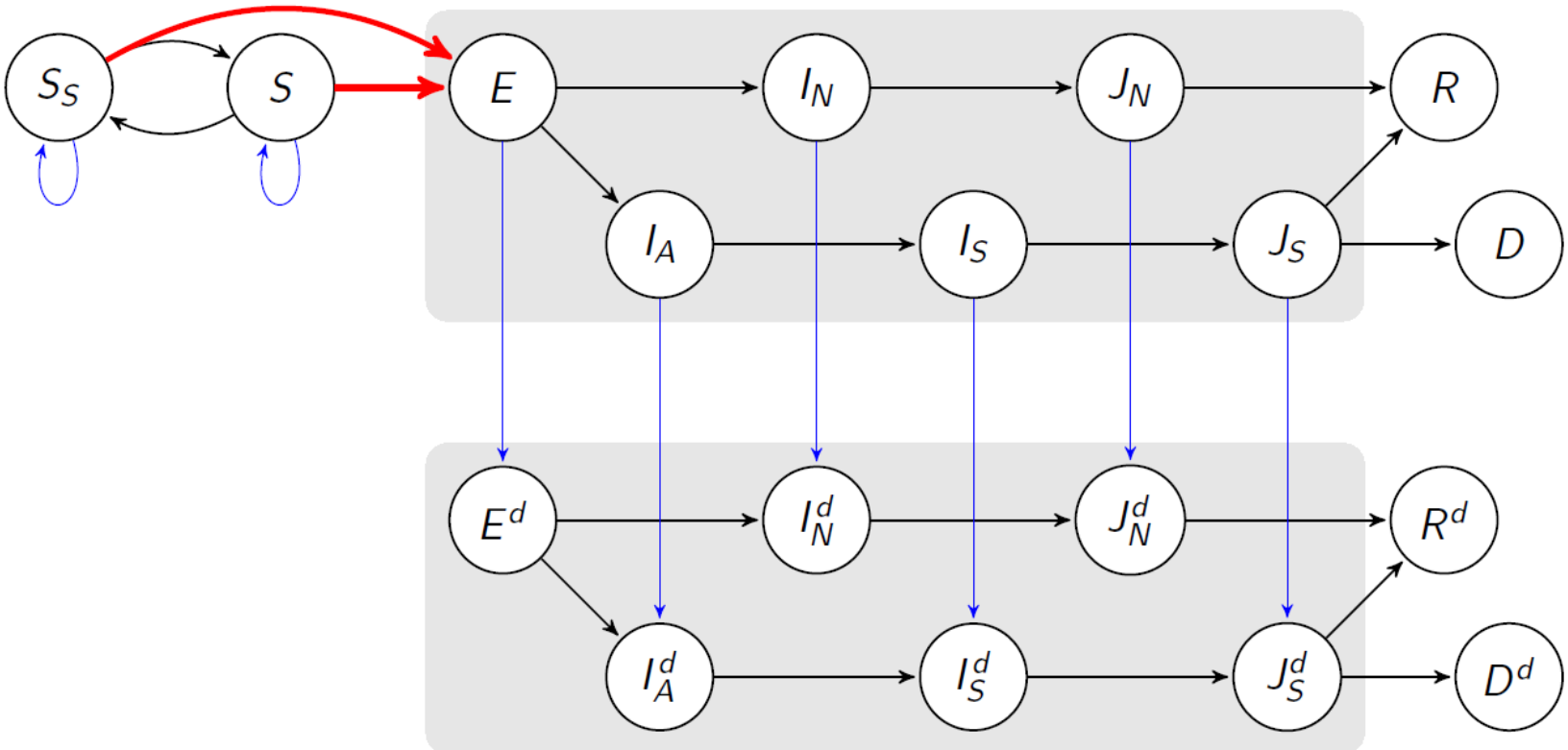

Base model
Policy module
Self-isolation
Testing
Contact-tracing
Graph

Base model - SEIR model

- Each individual is in exactly one of possible states
- Iterates on a daily basis
- Transition $S \rightarrow E$ is given by β and the contact graph
- Other transitions depends on parameters of the infection only

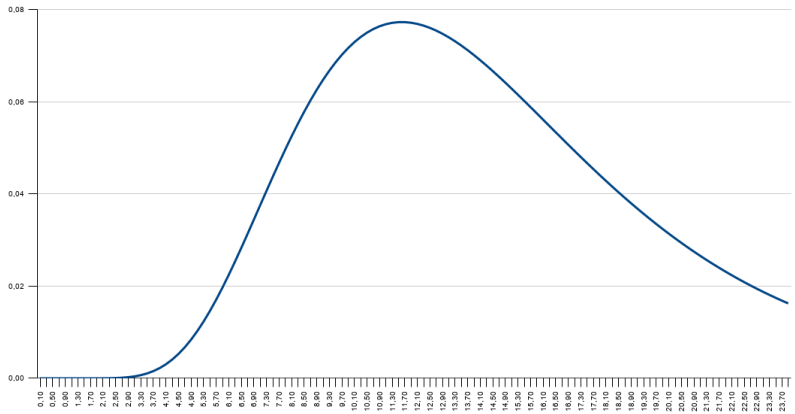


Base model - SEIR model

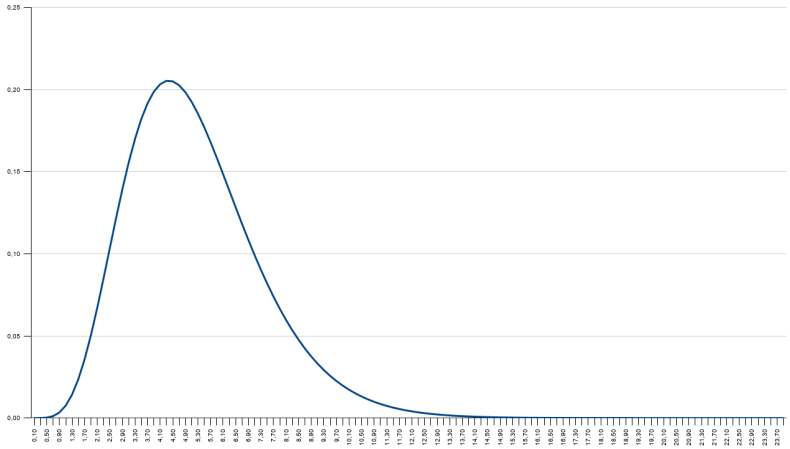


Base model - state durations

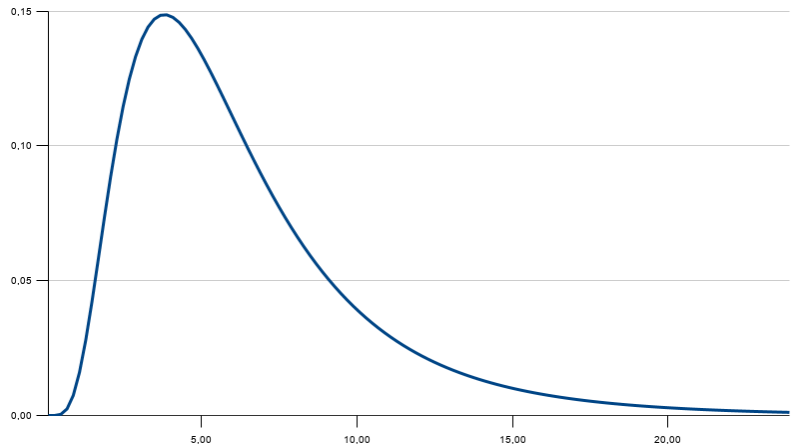
RNA positivity



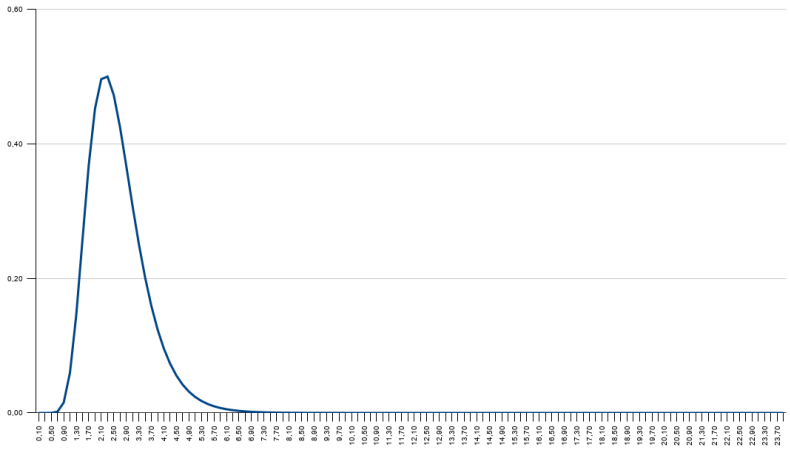
Infectiouness



Incubation

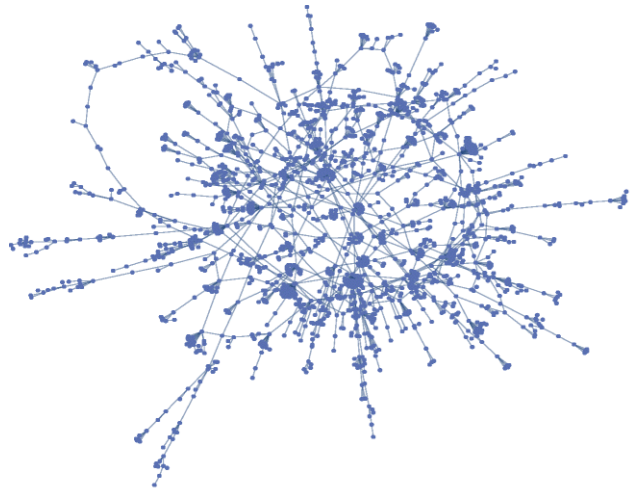


Presymptomatic time



Model M - graph

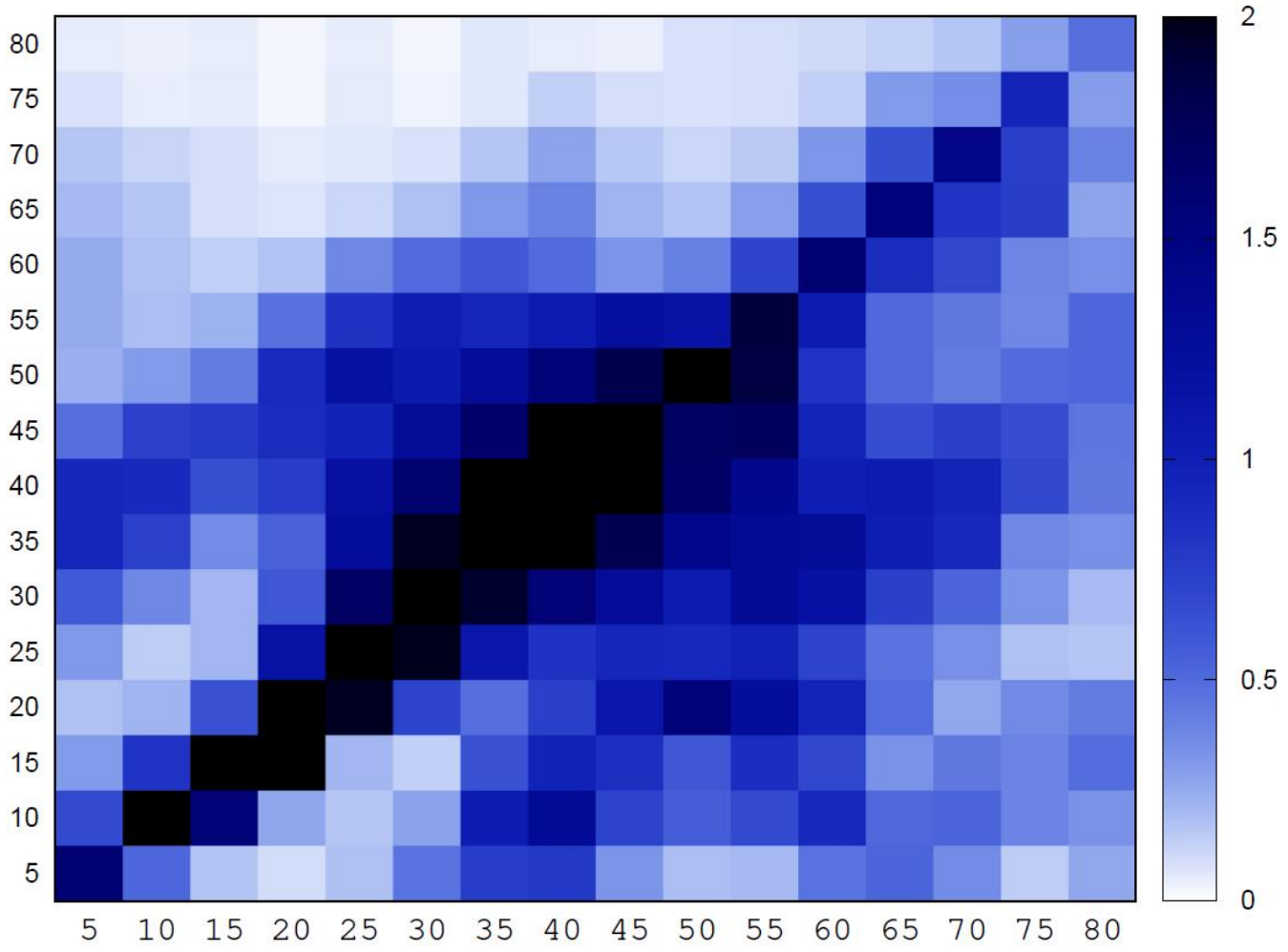
- Realistic graph
- Model of a real Czech county (Hodonín)
- Models contacts between people
- Multi-graph



- Data sources:
  - Czech Statistical Office
  - State Administration of Land Surveying and Cadastre
  - Ministry of Education, Youth and Sports
  - PAQ research, Median
  - Openstreet map
  - Expert knowledge
- Modified Barabasi-Albert algorithm

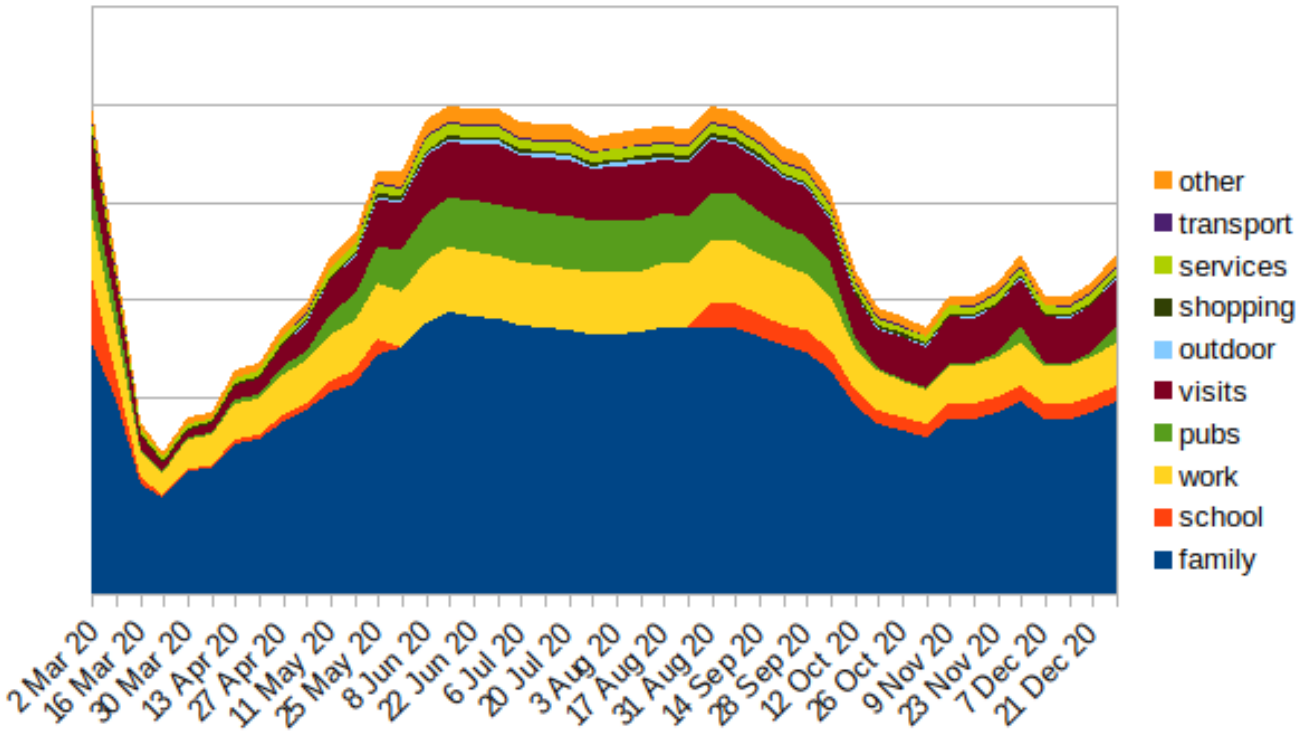
See Milan Zajíček's talk on youtube

Prem contact matrices



Prem et al. 2017

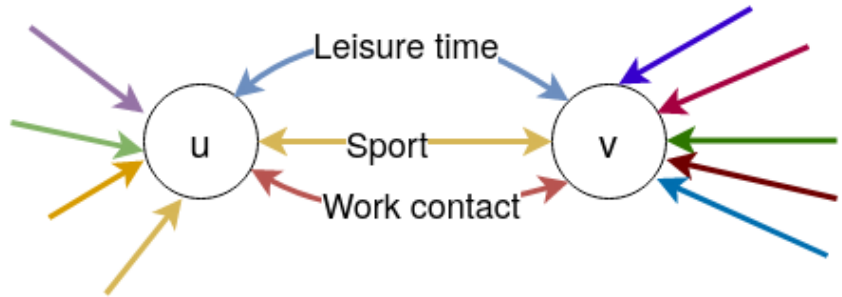
Contacts in time



PAQ, Life during pandemic

Model M - graph

- Multi-graph
- Edges organised in layers (family, work, school, etc.)
- 56 thousands nodes
- 2.8 millions edges
- 30 layers



- Each node represents one individual (agent)
- Node attributes - age, sex, work activity, commute time, location

Model M - graph

- Edges parameters:
  - Contact probability p
  - Intensity i
  - Layer type l
- Each day an edge is activated with the probability $w_l * p$ (w_l layer weight)
- Probability of infection transmission

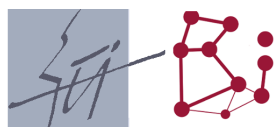
$$p_{S \to E}(e) = \begin{cases} \beta * i & \text{if the edge is active} \\ 0 & \text{otherwise} \end{cases}$$

Model M - policy module

- Implements various interventions and changes in people's behaviour
- Invoked on daily basis
- Modifies the graph
- Controls and change model parameters

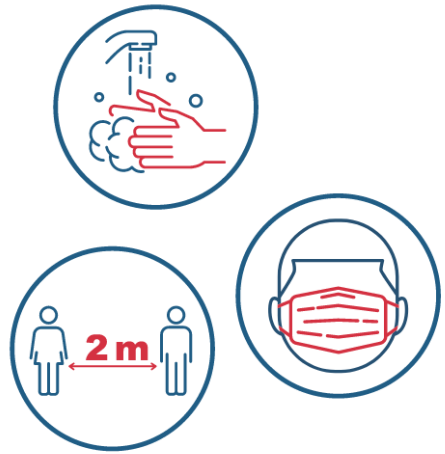
Interventions

- Protective measures - masks, hygiene, distancing, cautiousness
- Contact restrictions
  - Flat closures - closed schools, pubs, shops, etc.
  - Individual - isolation, quarantine



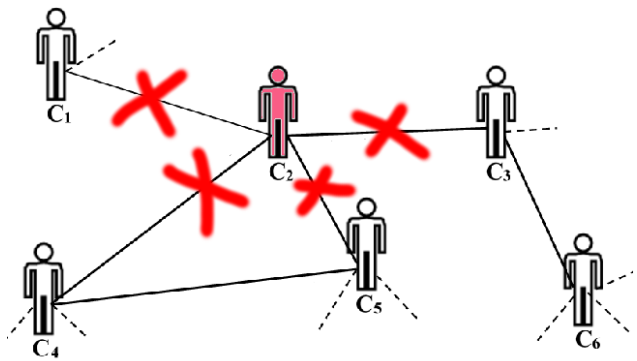
Model M - policies

- Protective measures
  - reduction of β

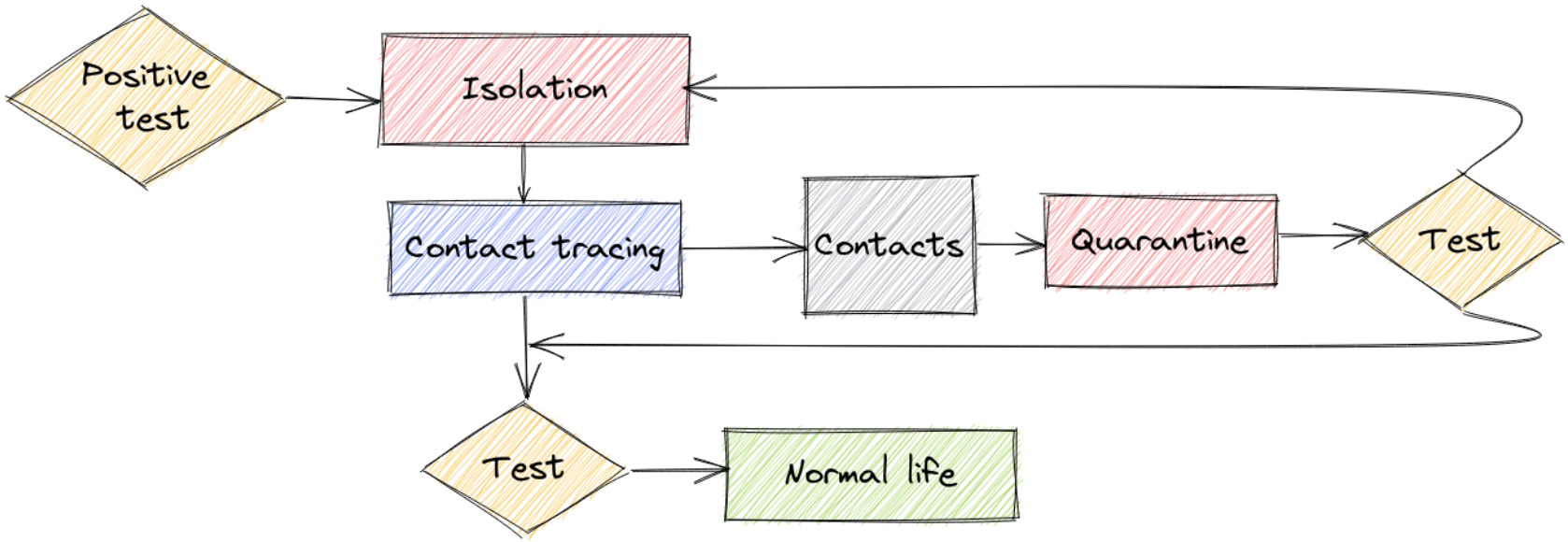


- Flat contact restrictions
  - Switching off whole layers

- Individual isolation
  - Testing, self-isolation – individuals with symptoms
  - Contact tracing – different levels of contact tracing (family, school & work, leisure time, others)



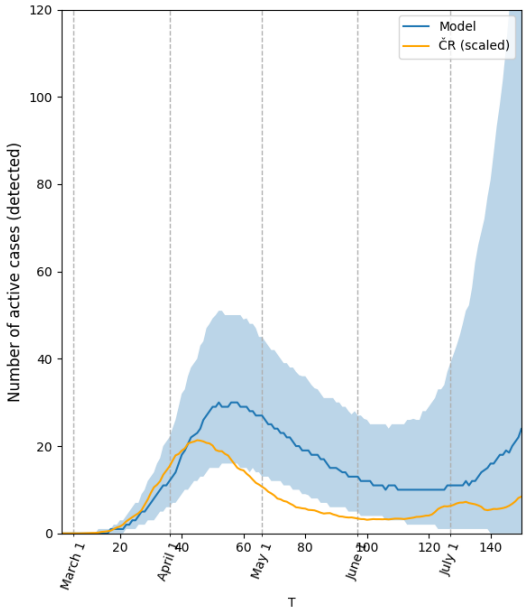
Model M - contact tracing

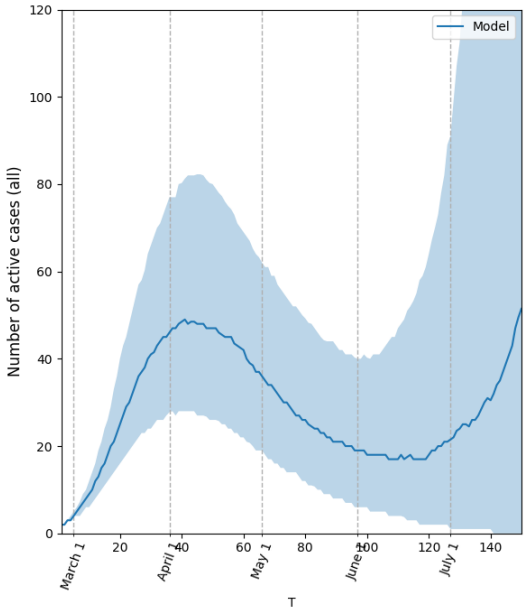


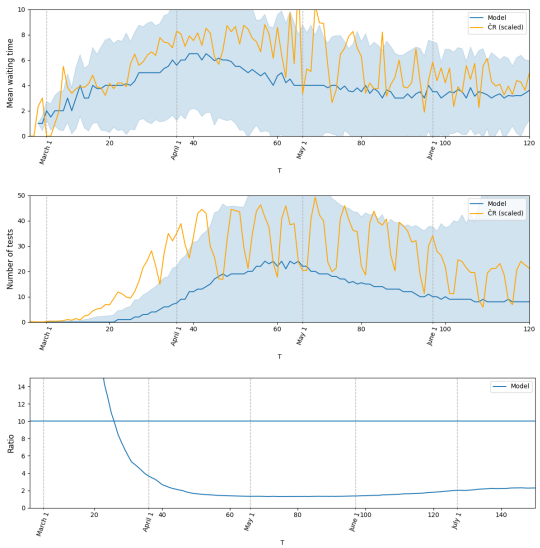
Experiments

- Calibration
- Contact tracing
- Schools
- Vaccination

Calibration





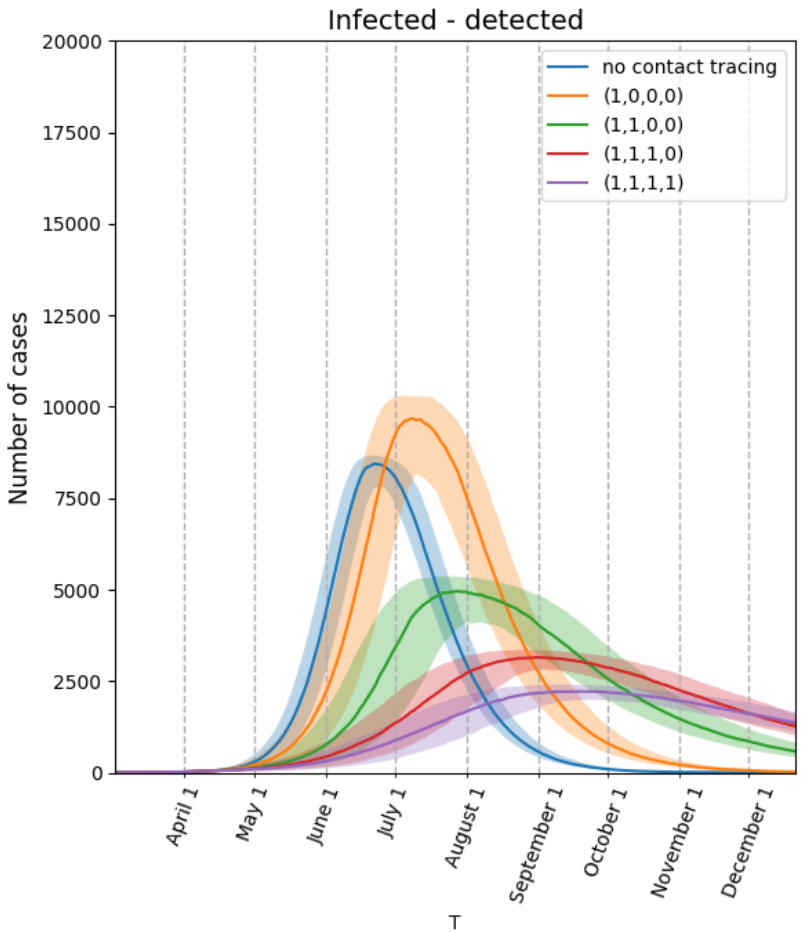


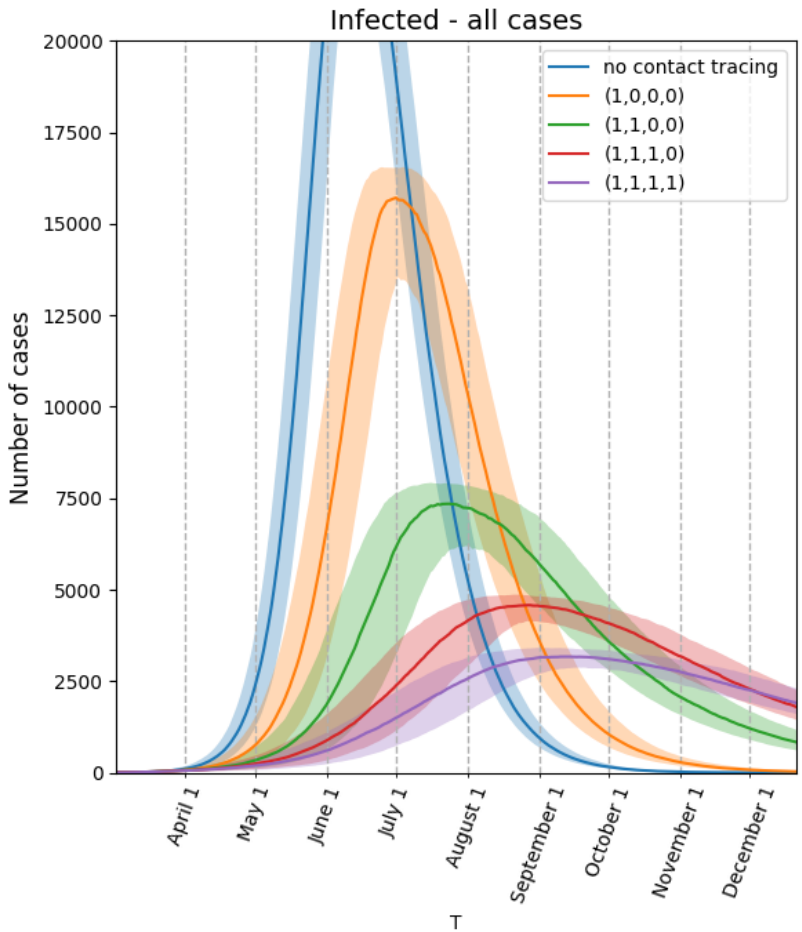
- Finding parameters to fit the history
- Using grid search and CMA-ES

Contact tracing

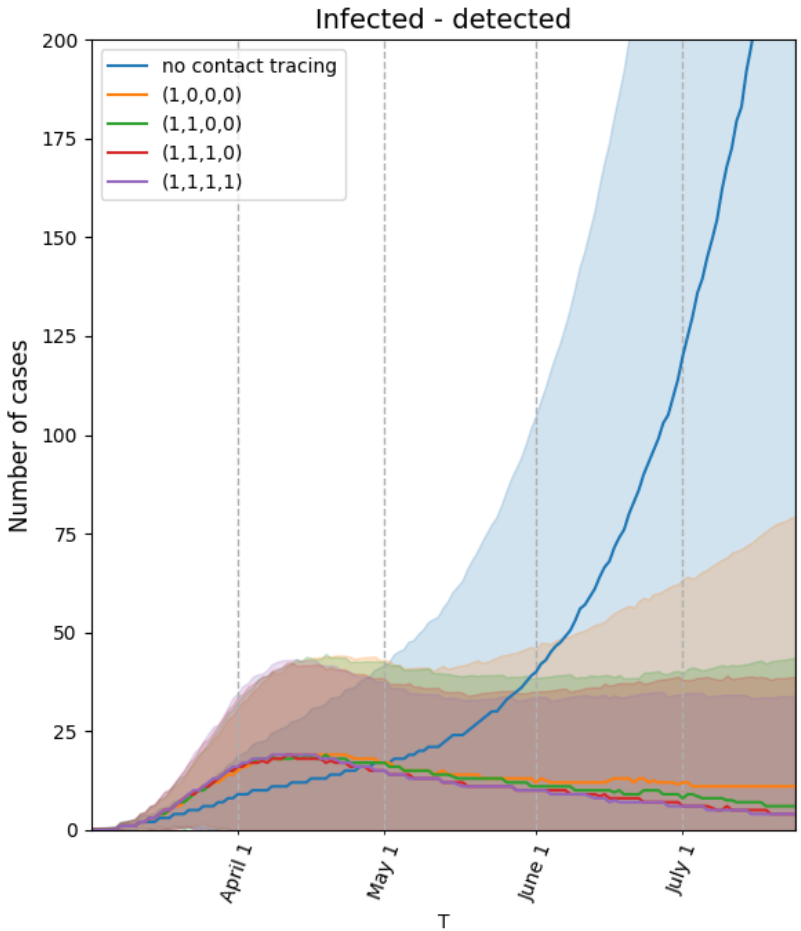
- Compare different levels of contact tracing – layers (family, school & work, leisure time, others)
- Two scenarios – with and without flat restrictions
- Flat restrictions corresponds to spring 2020 in the Czech Republic
- 1000 simulations for each setup (model is stochastic)

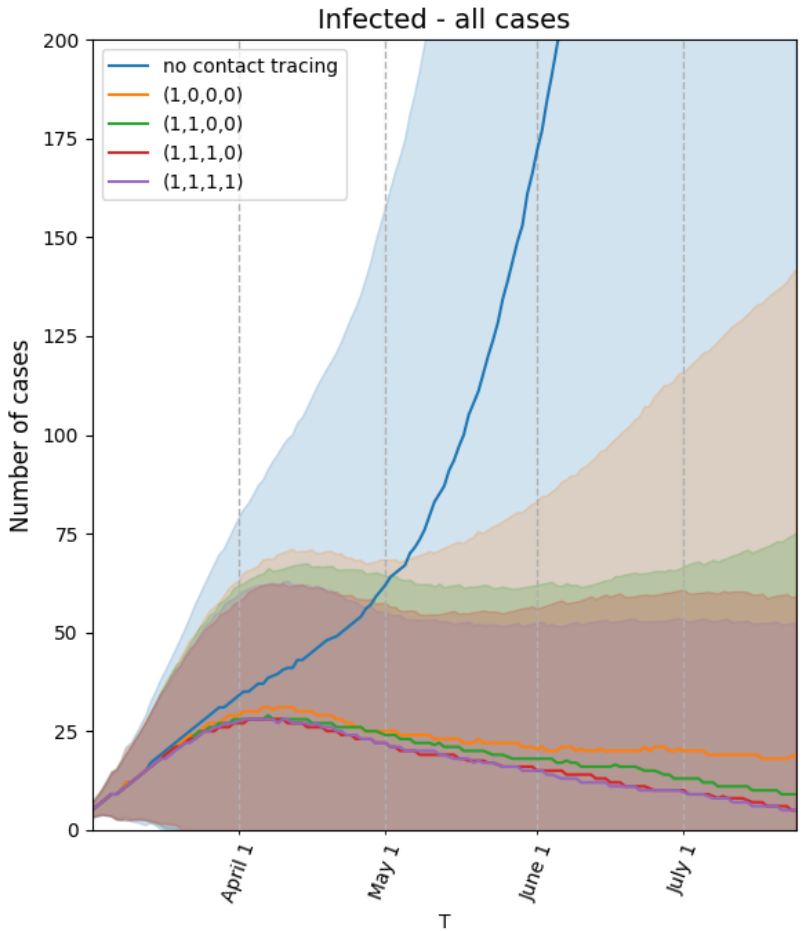
Different levels of contact tracing comparison



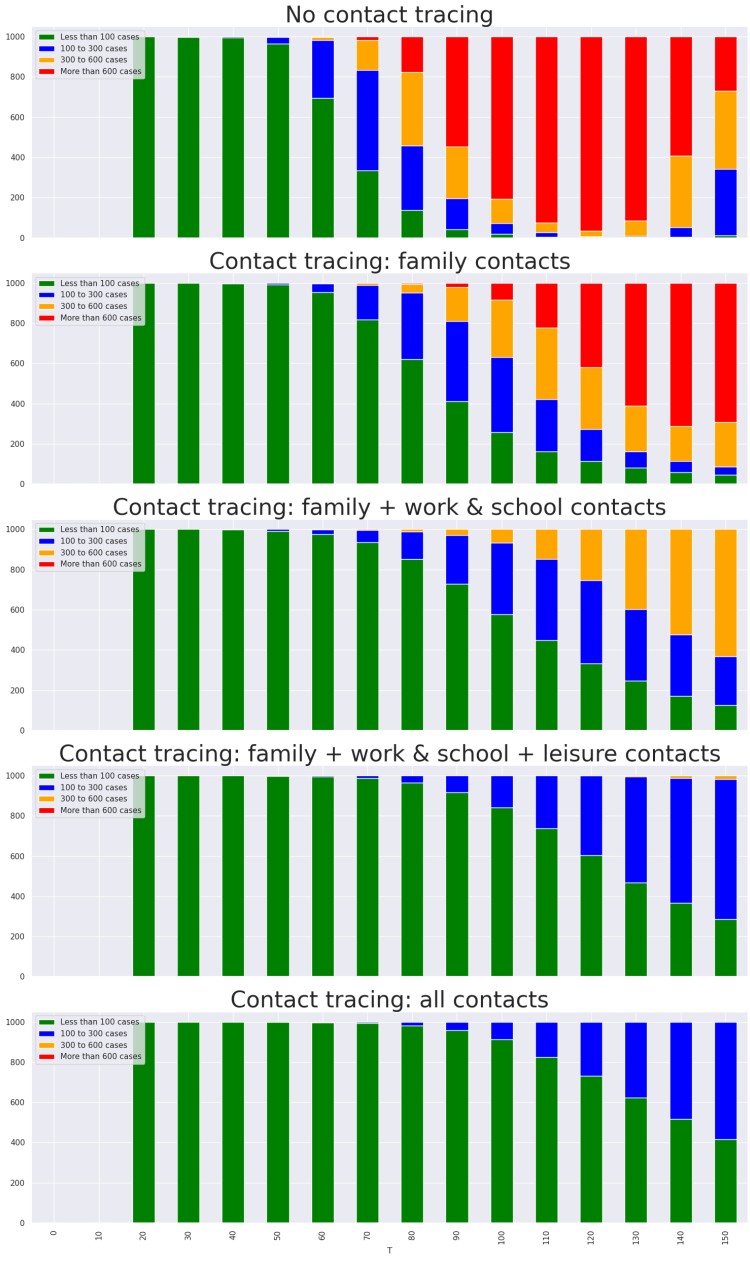


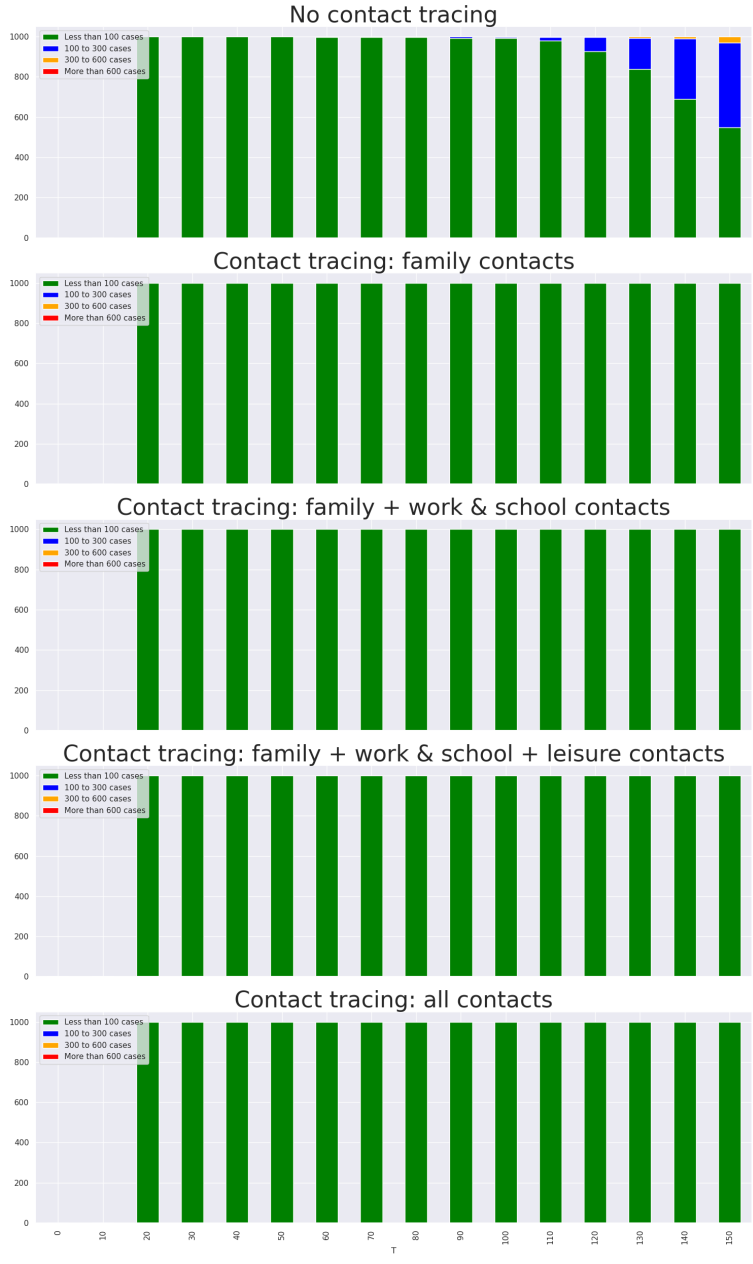
Different levels of contact tracing with flat closures





Distribution of individual simulation runs by epidemic level

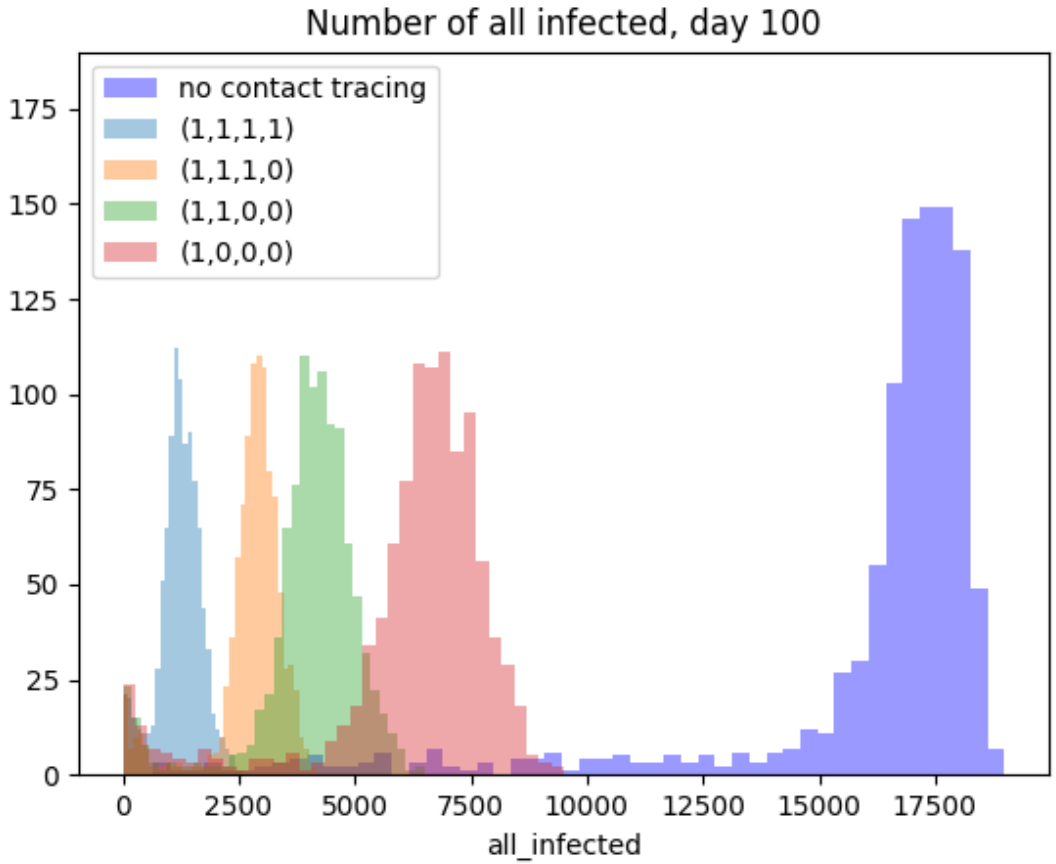




Histogram of simulation runs – scenario with a mass event

Experiment II

- A mass event
- Once a week
- 300 individuals
- 14 000 edges



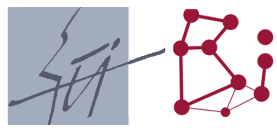
Experiments with school environment

Schools

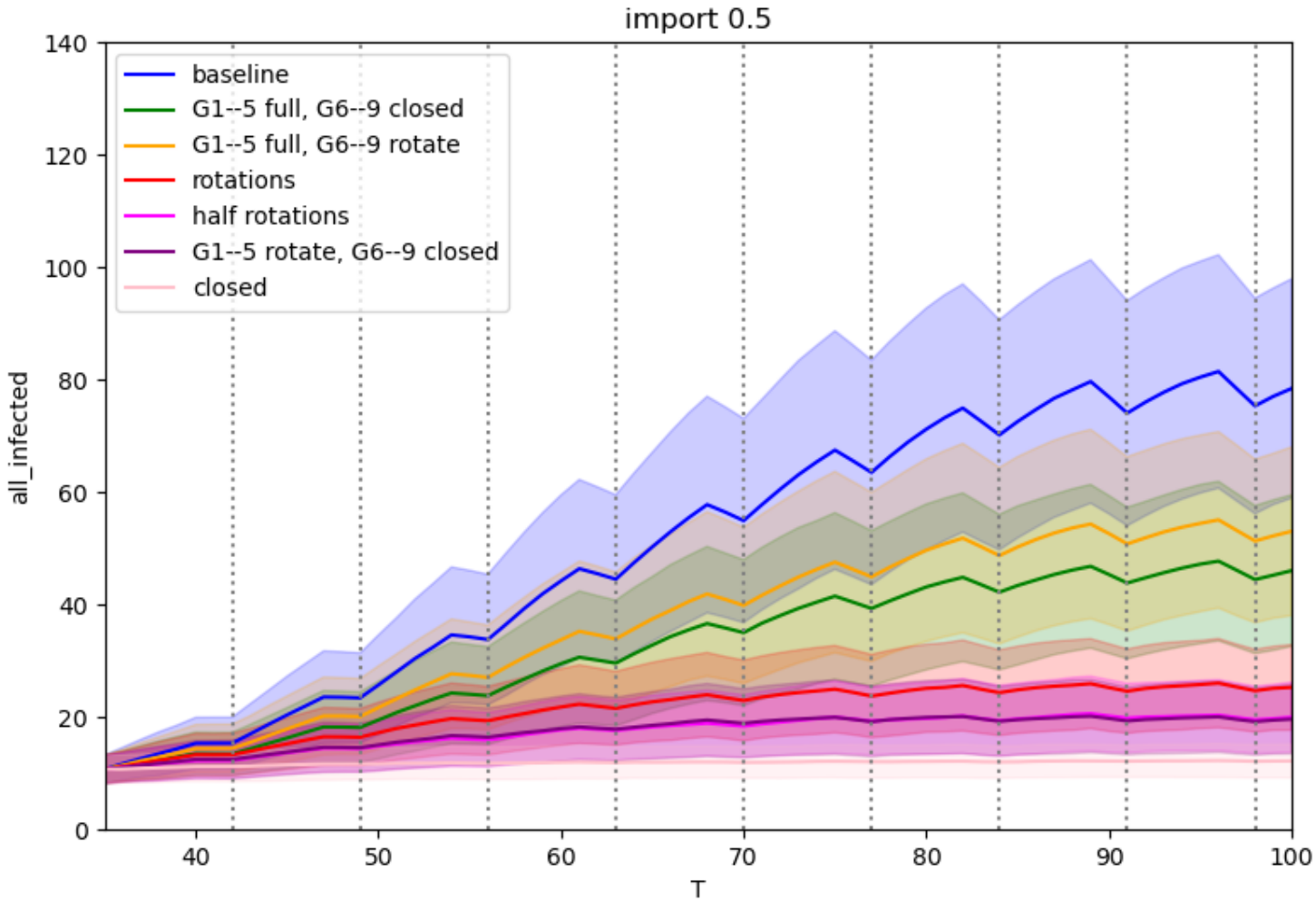
- In cooperation with Ministry of Education, Youth, and Sports
- Need for safe mode of school attandance

- An alternative graph, model of a real school
- Based on sociological survey
- 650 nodes (teachers and pupils), 70 layers of edges

- Goals is to study various interventions
- Partial closures
- Week alternations
- Testing

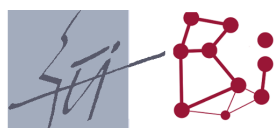


Rotation Scenarios

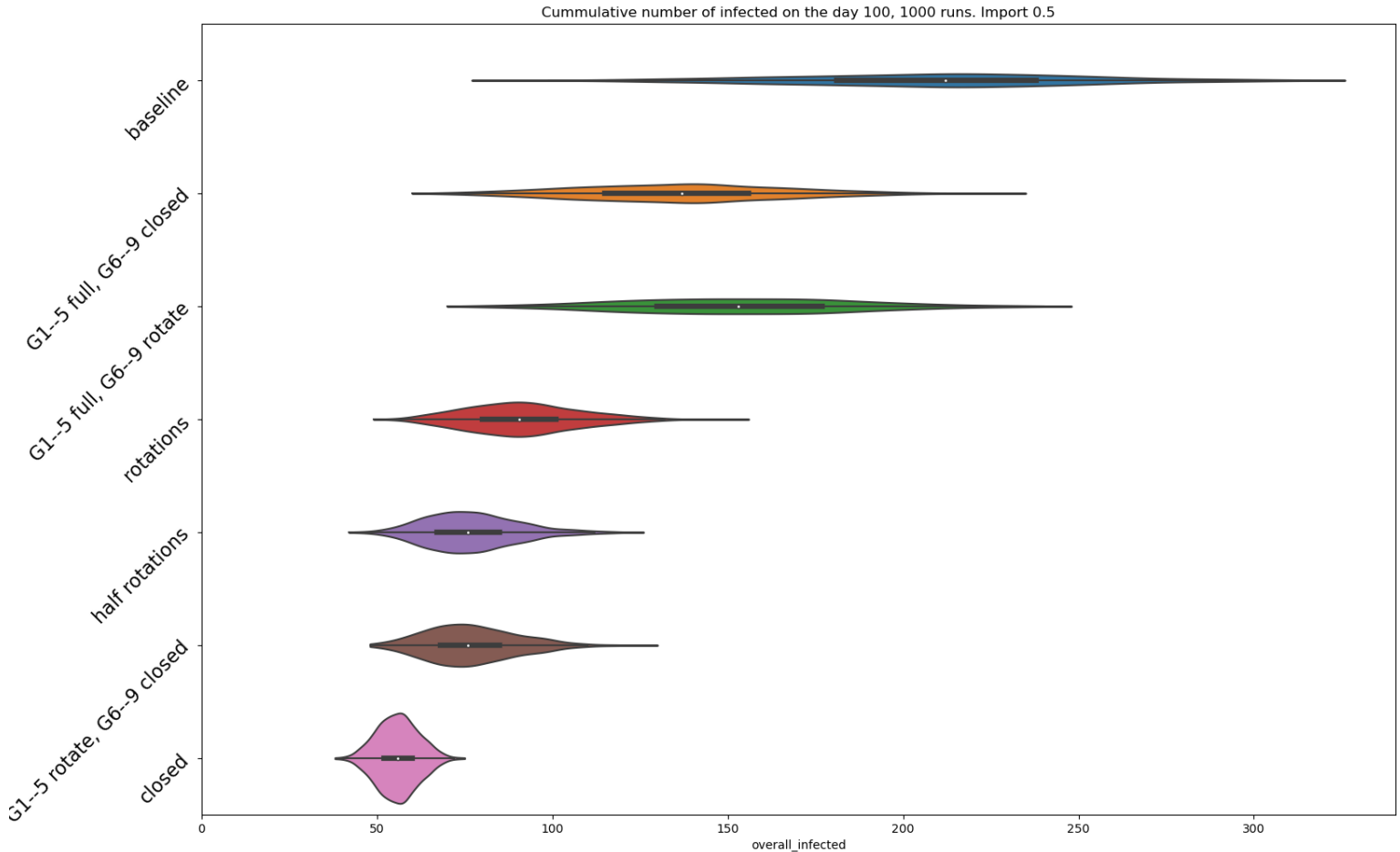


Rotation Scenarios

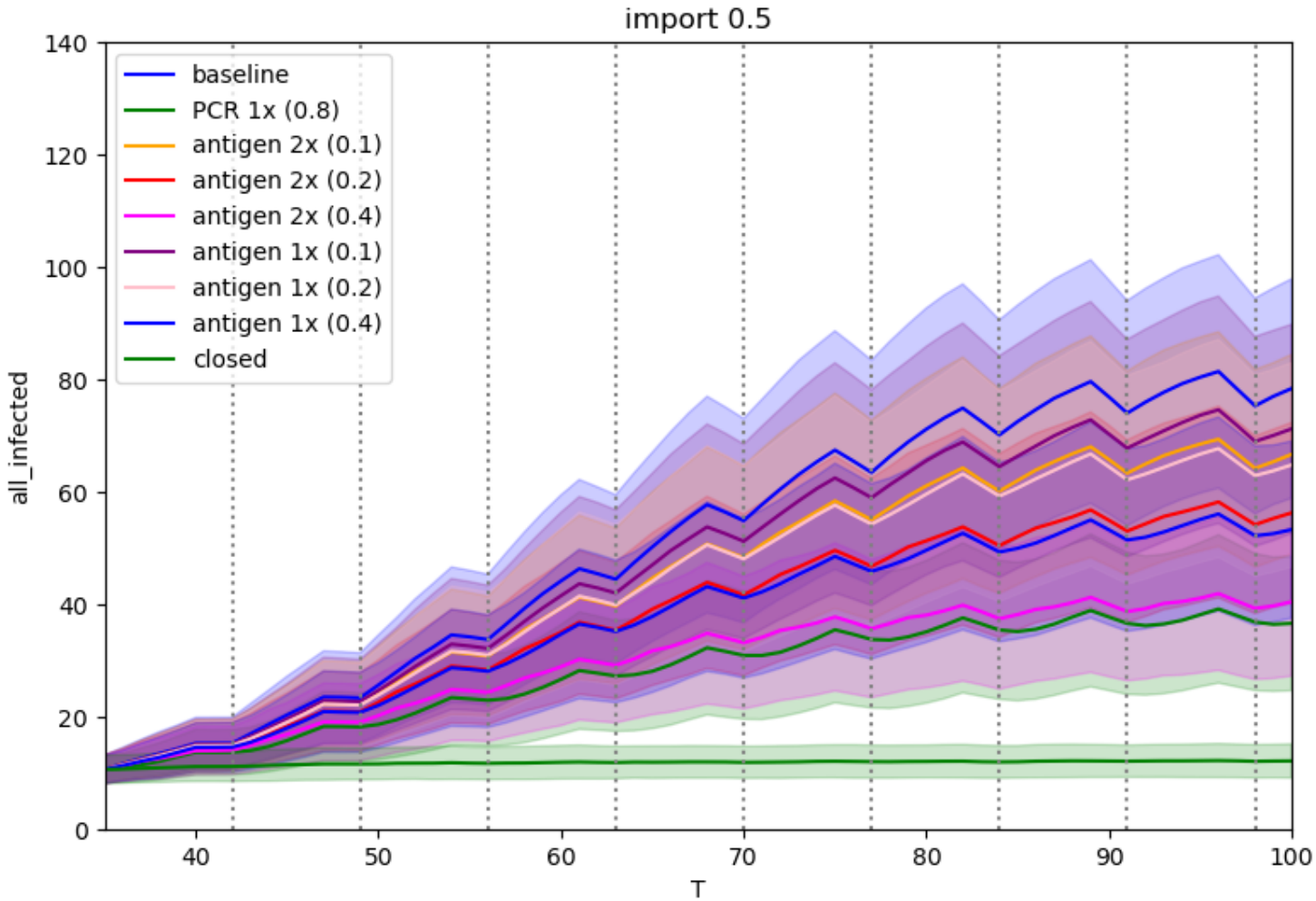
	import			
	0.1	0.25	0.5	1.0
baseline	100.00	100.00	100.00	100.00
G1–5 full, G6–9 closed	50.67	54.67	52.98	54.38
G1–5 full, G6–9 rotate	60.19	63.87	63.92	64.46
rotations	18.93	21.94	22.69	24.79
half rotations	13.18	12.57	14.02	15.42
G1–5 rotate, G6–9 closed	12.17	12.47	13.83	15.32
closed	0.00	0.00	0.00	0.00



Rotations - violin plots



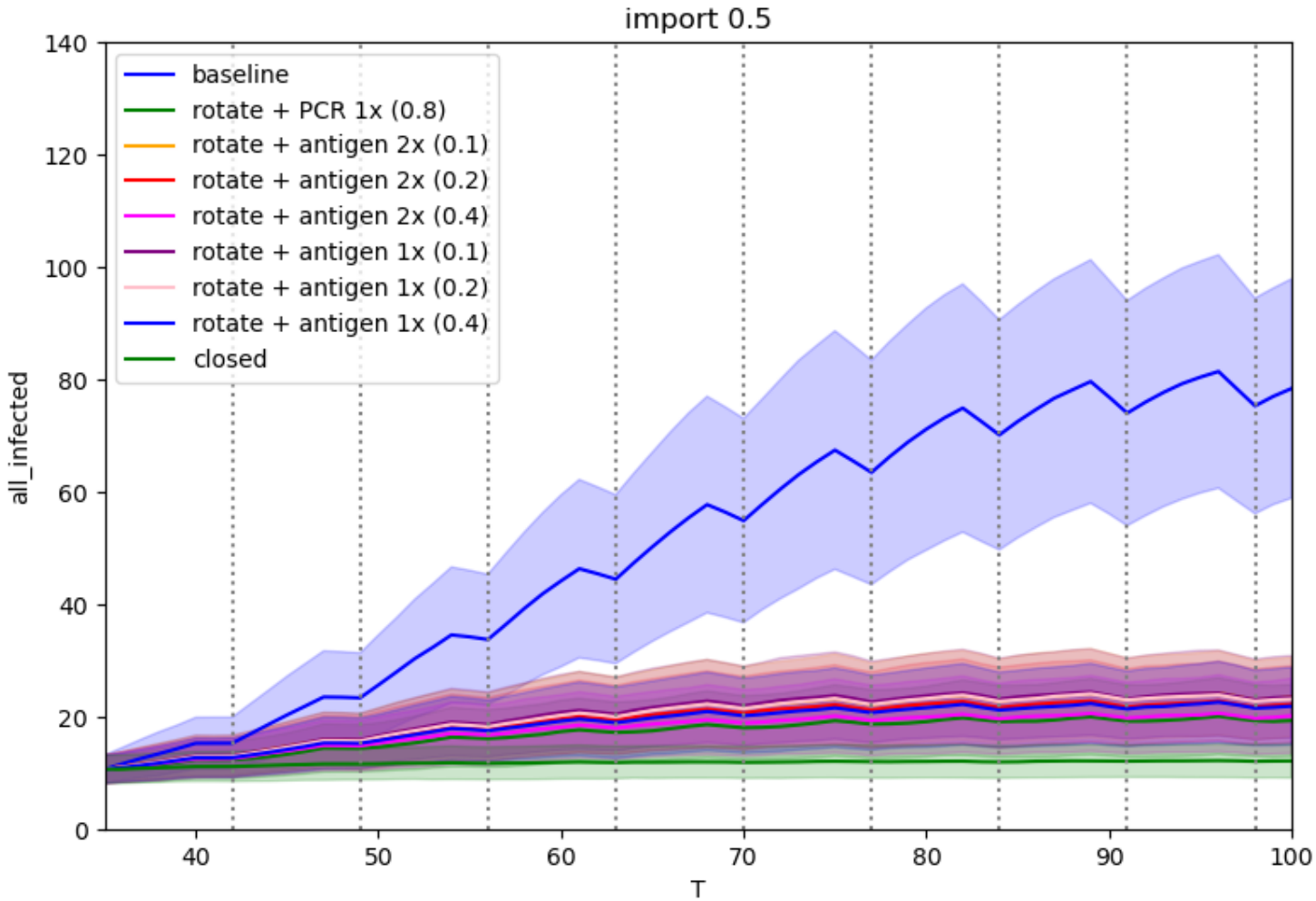
Testing scenarios



Testing scenarios

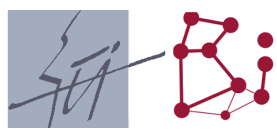
	import			
	0.1	0.25	0.5	1.0
baseline	100.00	100.00	100.00	100.00
PCR test once	38.34	42.26	42.26	44.59
antigen test twice (0.1)	83.43	83.28	83.60	85.27
antigen test twice (0.2)	64.02	67.91	67.55	71.33
antigen test twice (0.4)	43.48	44.42	45.98	48.43
antigen test once (0.1)	90.86	93.36	91.26	92.43
antigen test once (0.2)	79.34	82.01	82.13	83.74
antigen test once (0.4)	61.27	64.28	65.81	68.77
closed	0.00	0.00	0.00	0.00

Rotations + Tests



Rotations + Tests

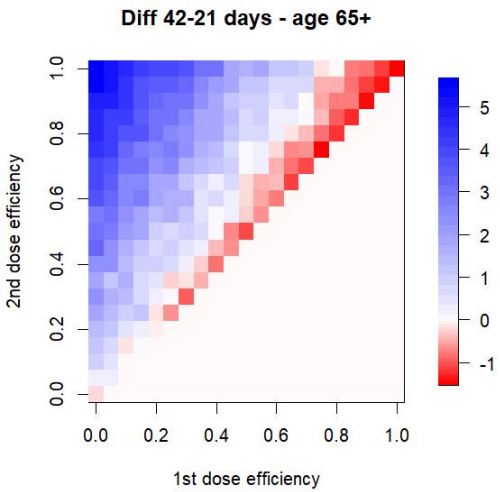
	import			
	0.1	0.25	0.5	1.0
baseline	100.00	100.00	100.00	100.00
rotation + PCR test once	12.77	13.12	12.95	14.76
rotation + antigen twice (0.1)	18.46	19.45	19.76	22.50
rotation + antigen twice (0.2)	16.65	16.96	17.87	20.51
rotation + antigen twice (0.4)	14.76	14.11	14.25	16.28
rotation + antigen once (0.1)	19.51	20.24	20.61	23.63
rotation + antigen once (0.2)	18.70	19.51	19.80	22.23
rotation + antigen once (0.4)	16.92	16.38	16.94	19.49
closed	0.00	0.00	0.00	0.00

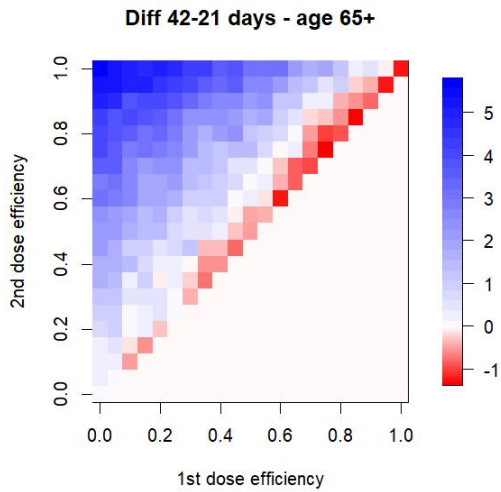


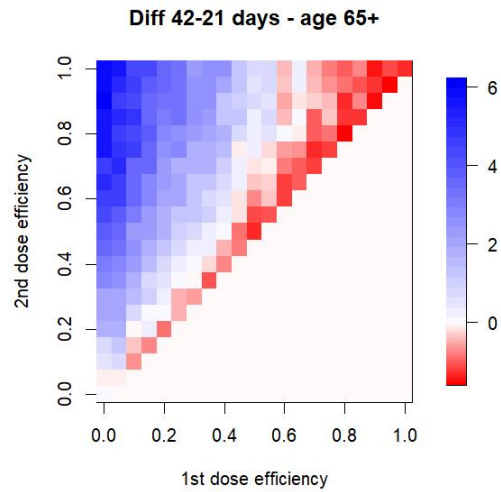
Experiments with vaccination

- Policy implementing vaccination
- Various efficacy of vaccination
- Various effects of vaccination
- Comparing different scenarious of second dose delays

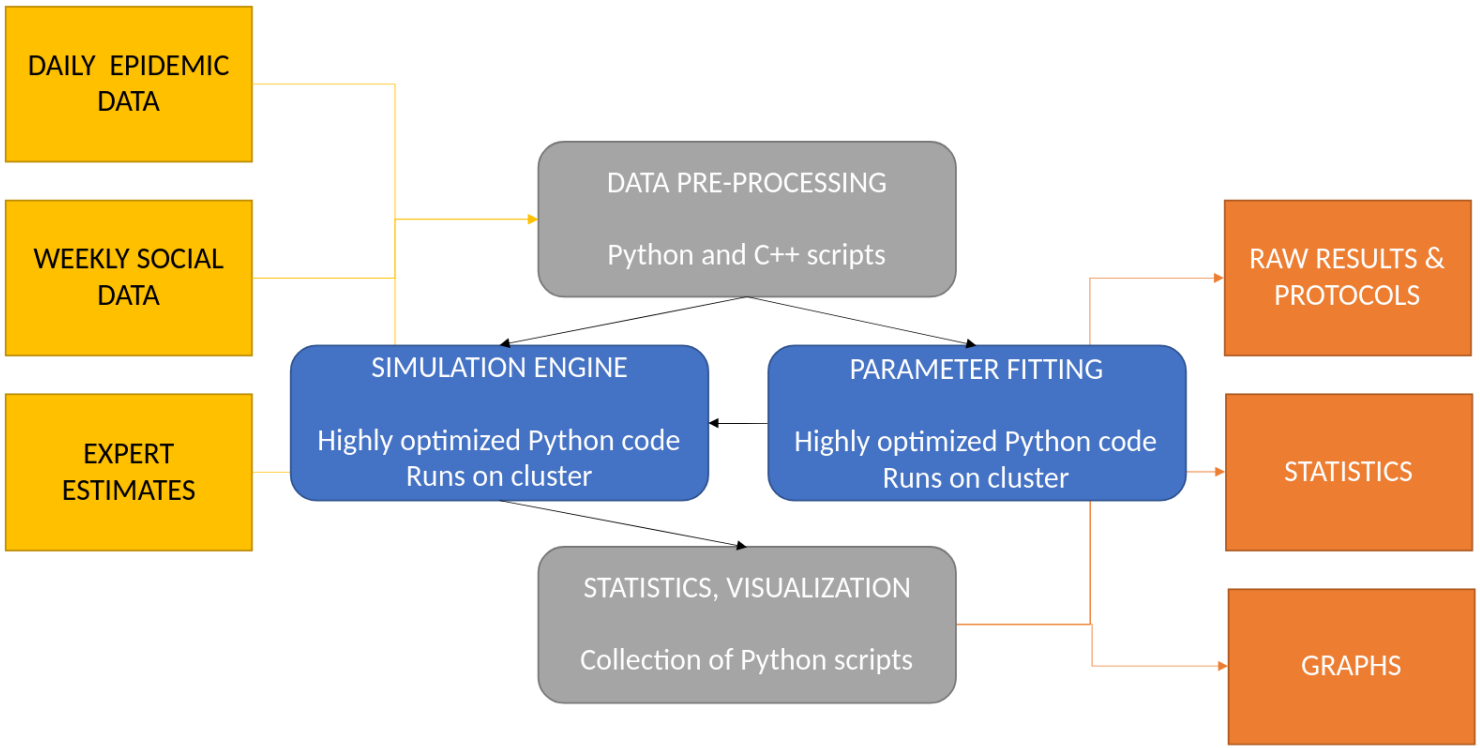
Experiments with vaccination







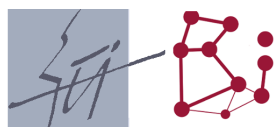
Software



github.com/epicity-cz/model-m

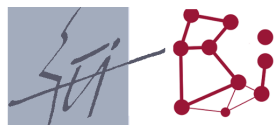
Papers

- Berec et al. Delays, masks, the elderly, and schools: first Covid-19 wave in the Czech Republic, Bulletin of Mathematical Biology volume 84, Article number: 75 (2022) https://doi.org/10.1007/s11538-022-01031-5
- Berec et al. Importance of vaccine action and availability and epidemic severity for delaying the second vaccine dose, Scientific Reports volume 12, Article number: 7638 (2022) https://doi.org/10.1038/s41598-022-11250-4
- Brom et al. Rotation-based schedules in elementary schools to prevent COVID-19 spread: A simulation study. https://doi.org/10.1101/2021.06.28.21259628
- Berec et al. On the Contact Tracing for COVID-19: A simulation study. (in review, Epidemics, Elsevier)



Papers

- Berec et al. Model-M: An agent-based epidemic model of a middle-sized municipality. https://doi.org/10.1101/2021.05.13.21257139
- Vidnerová et al. Simulation of non-pharmaceutical interventions in an agent based epidemic model. Proceedings of the 21st Conference Information Technologies – Applications and Theory (ITAT 2021). https://ics.upjs.sk/ antoni/ceur-ws.org/Vol-0000/paper12.pdf
- Monography in Czech in print. To appear soon.



Conclusion

Summary

- Agent based epidemic model with a realistic graph
- Enables simulation of various interventions on individual level
- Modular and extensible (different graphs, vaccination, etc.)

Thank you! Questions?