DLR

A SPATIAL-HYBRID MODEL FOR INFECTIOUS DISEASE DYNAMICS

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Predictive Simulation Software
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Joint work with René Schmieding and Martin Kühn

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Modeling infectious diseases

Agent-based models (ABM)

- High level of detail possible
- Ability to create heterogenous agents and get results on individual level
- Computational cost depends on the number of agents

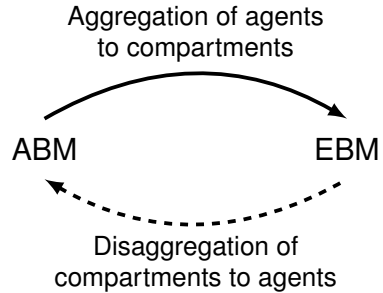
Equation-based models (EBM)

- Limited level of detail due to compartmental representation
- Assumes homogenous and well-mixed population
- Computationally efficient as runtime does not depend on population size

Hybridization Approach

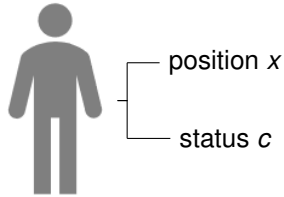
- Spatial hybridization combining an agent-based (focus region) and a piecewise equation-based model (surrounding regions)

Detailed results in a **focus region** while considering the influence of **neighboring regions** in a **runtime efficient** manner.



Agent-based model*

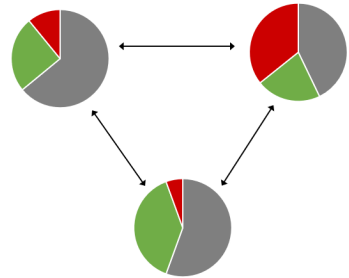
- Agent $\alpha = (x, c) \in \Omega \times \Gamma$
  - $\Omega \subset \mathbb{R}^2$: Domain agents move in
  - $\Gamma = (c_1, c_2, \ldots, c_{n_C})$: Set of infection states (status)
- Markov process $(Y(t))_{t \in T}$ describes evolution of system state over time with $Y(t) = (X(t), C(t))$
- Agents' movement: Diffusion process
- Status adoptions: Poisson processes given by adoption rate functions



*Winkelmann, S., Zonker, J., Schütte, C., Conrad, N.D.: Mathematical modeling of spatio-temporal population dynamics and application to epidemic spreading. Mathematical Biosciences 336, 108619 (2021), https://www.sciencedirect.com/science/article/pii/S0025556421000614

Piecewise equation-based model* (PEBM)

- Subregions S_m, $m = 1, .., M$ with subpopulations
- Domain $\Omega = \bigcup_{m=1}^{M} S_m$
- Movement: Stochastic jumps between subpopulations given by transition rates
- Status adoption dynamics: Set of ordinary differential equations for every subpopulation



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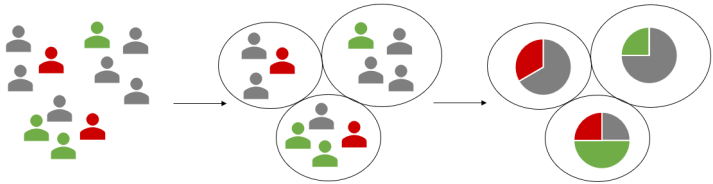
Definition of regions for PEBM: From ABM to PEBM*

- Metastable regions of diffusion process as subregions such that $\Omega = \bigcup_{m=1}^{M} S_m$
- Position: $x \in \mathbb{R}^2 \mapsto x \in \{1, .., M\}$
- Spatial transitions are rare compared to status adoptions: Approximation of jump processes by deterministic equations



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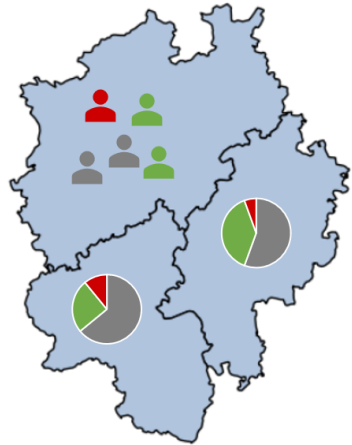
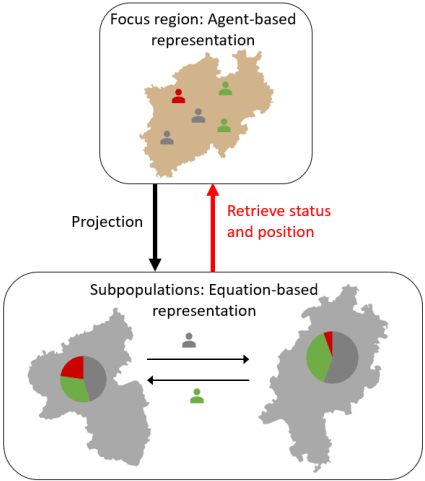
Hybrid model

- Usage of model depends on region
- Regular exchange between ABM and PEBM



Using geodata from https://gdz.bkg.bund.de/index.php/default/verwaltungsgebiete-1-2-500-000-stand-31-12-vg2500-12-31.html

Hybrid model: Exchange between models



ABM → PEBM:

- Unique mapping to subpopulation according to agent's position

PEBM → ABM:

- Loss of information: Position can be anywhere in the focus region
- Agent is created in the center of the focus region

Using geodata from https://gdz.bkg.bund.de/index.php/default/verwaltungsgebiete-1-2-500-000-stand-31-12-vg2500-12-31.html

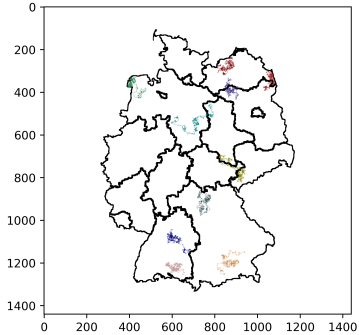
Application: Hybrid model for Germany

Domain and agents' movement

- Potential $P : \Omega \mapsto \mathbb{R}$ is given by Portable Gray Map of German federal states with a Gaussian curve on the borders
- North Rhine-Westphalia as focus region
- Diffusion process

$$\frac{dX(t)}{dt} = -\nabla P(X(t)) + \sigma\xi(t) \,, \qquad (1)$$

σ diffusion constant, $\xi(t)$ a white noise process



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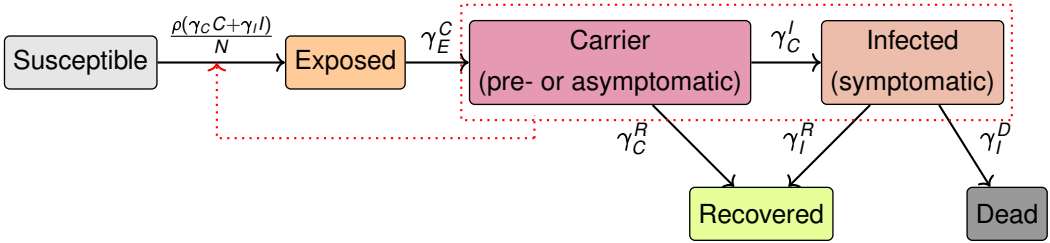
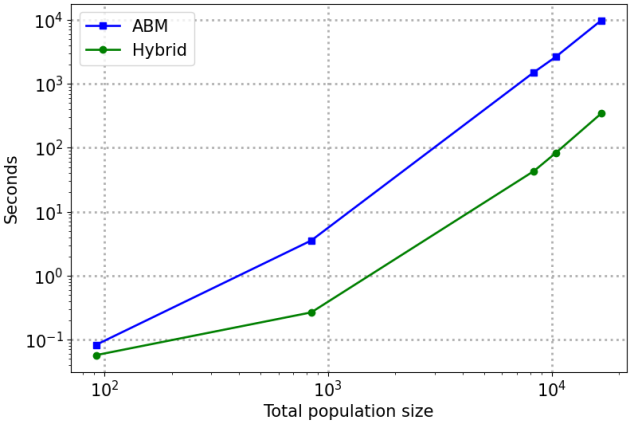
Application: Hybrid model for Germany

Transmission model

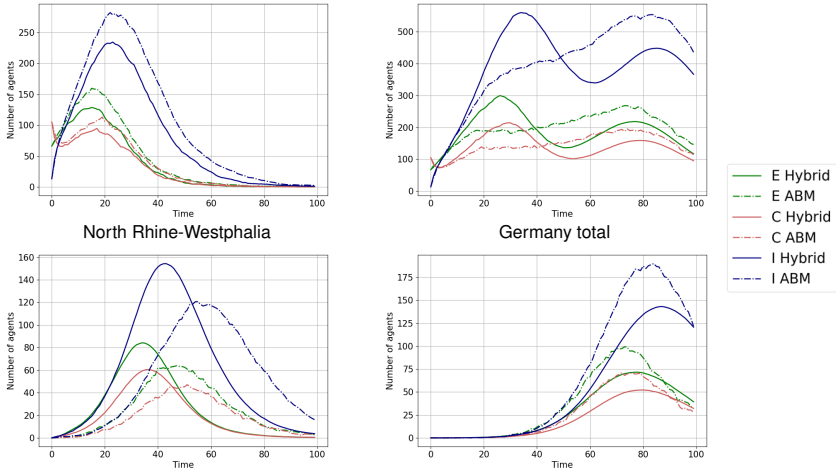


Runtime results hybridization



- ABM runtime lies in $\mathcal{O}({n_a}^2)$, n_a number of agents
- Hybrid model reduces runtime by 96.5% for $\approx$ 17000 agents compared to ABM

Simulation results hybridization



Conclusion

- Spatial resolution is important
- ABMs can model on individual level but are costly
- Influence from other regions should be considered cost effectively
- Hybrid model can save more than 90% of cost and resources
- Parameter fitting ongoing

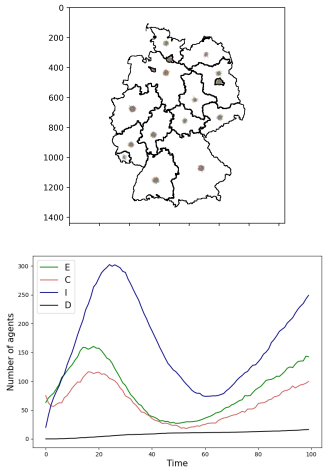
- Github repository: https://github.com/DLR-SC/memilio, code for hybrid model on fork https://github.com/reneSchm/memilio 
- To be submitted: Julia Bicker, René Schmieding, Martin Kühn: A spatial-hybrid model for infectious disease dynamics (2023)

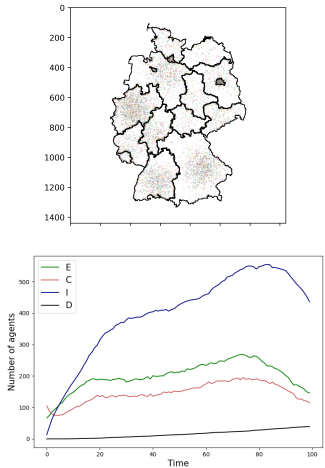
Thank you for your attention!

Appendix

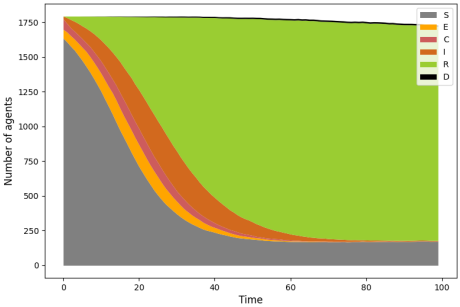
Simulation results ABM

- Agents' position initialization influences model results

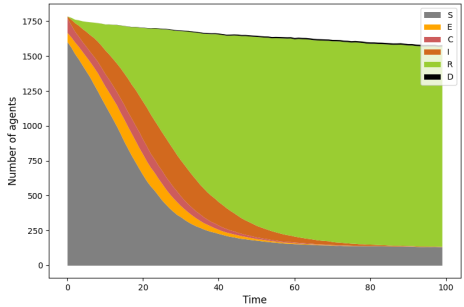




Simulation results ABM - Focus region

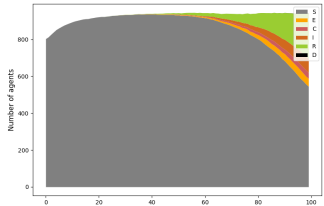


Initialization 1

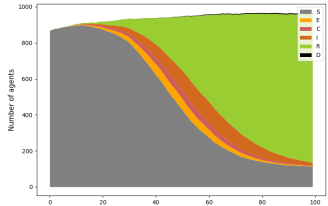


Initialization 2

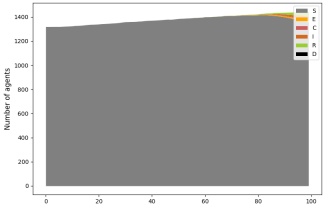
Simulation results ABM - Surrounding region



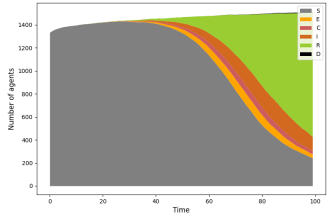
Lower Saxony initialization 1



Lower Saxony initialization 2



Bavaria initialization 1



Bavaria initialization 2