



From SIR to Agent-Based Models

Bridging Biological Heterogeneity
and Epidemic Decision-Making

Lessons from COVID-19 for Future Epidemics

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Minisymposium MS3



Facultad
de Ciencias
Básicas

dm_{2a}
Doctorado en Modelamiento
Matemático Aplicado

The connection to mathematical immunology



Which biological differences change the preferred policy?

Conceptual bridge for this talk.

A minimal within-host starting point

Illustrative model for the bridge between scales

$$\dot{T}_i = -k_i V_i T_i,$$

$$\dot{Y}_i = k_i V_i T_i - \delta_i Y_i,$$

$$\dot{V}_i = p_i Y_i - c_i V_i.$$

T_i : susceptible target cells

Y_i : infected cells

V_i : viral concentration

k_i, p_i, δ_i, c_i : infection, production and clearance parameters.

Immune mechanisms can change clearance and cell susceptibility.

Explicit innate and adaptive responses require additional states.

Standard target-cell model, used here as a schematic. For a SARS-CoV-2 model linking shedding and transmission: Goyal et al. (2021), eLife 10:e63537.

Viral dynamics need a transmission interface

Proposed coupling

$$\lambda_i(t) = s_i(t) \sum_{j \neq i} a_{ij}(t) g(V_j(\tau_j))$$

Component	Meaning	Relevant information
$s_i(t)$	Recipient susceptibility	Immune history
$a_{ij}(t)$	Contact intensity	Household, school, mobility
$g(V_j)$	Infectiousness per contact	Shedding and infectivity

τ_j : time since infection. a_{ij} : contacts/day. λ_i : daily hazard.

The viral-load-to-infectiousness map needs its own evidence.

SIR makes the population average explicit

$$\dot{S} = -\beta \frac{SI}{N},$$

$$\dot{I} = \beta \frac{SI}{N} - \gamma I,$$

$$\dot{R} = \gamma I.$$

$$\beta = c p$$

Contact rate c and transmission probability p .

$$\mathcal{R}_0 = \beta / \gamma$$

For a fully susceptible, homogeneously mixing population.

An effective parameter combines several mechanisms.

Standard closed-population SIR model with frequency-dependent transmission.

Model structure follows the decision

Representation	What it makes explicit	Useful decision question
Compartmental model	Disease states and population flows	How does transmission affect hospital demand?
System dynamics	Stocks, flows and feedbacks, including behaviour	How do delays and responses interact?
Agent-based model	Individual attributes and contact settings	Which people and locations does a policy affect?

Compartments can be heterogeneous. Agent models can use simple biology. System dynamics can include compartmental equations.



Assessment of event-triggered policies of nonpharmaceutical interventions based on epidemiological indicators

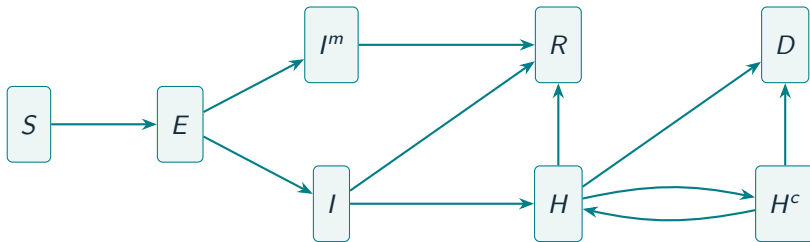
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The published model separates clinical pathways



E : exposed, infectious at a lower rate. I^m : mild/subclinical, undetected.

I : detected infected. H : hospital. H^c : ICU. D : deaths.

Clinical resolution makes ICU-based policies computable.

Castillo-Laborde et al. (2021), J. Math. Biol., Eq. (7) and Fig. 4. Redrawn topology. Chile case: one age class, no explicit immunity or vaccination dynamics.

Interventions modify specific transmission terms

$$\hat{\Lambda}(x_t, u_t) = \frac{(1 - u_t)(\beta_E E_t + \beta_{I^m} I_t^m) + \hat{\delta} \beta_I I_t}{N - D_t}$$

$$S_{t+1} = S_t - \hat{\Lambda}(x_t, u_t) S_t,$$

$$E_{t+1} = E_t + \hat{\Lambda}(x_t, u_t) S_t - \gamma_E E_t.$$

$u_t \in [0, 1 - \hat{\delta}]$: contact reduction for E and I^m .

Detected cases already have isolation factor $\hat{\delta} = 0.2$. Hospital transmission is neglected.

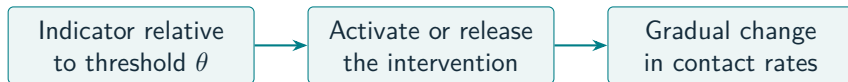
A policy acts through a specified mechanism.

Castillo-Laborde et al. (2021), Chile case. Daily discrete-time model.

Event-triggered policies use recent observations

$$O_1(x_t) = H_t^c, \quad O_2(x_t) = \frac{10^5}{N}(I_t + H_t + H_t^c)$$

$$\mathcal{I}_a(t) = \frac{1}{\Delta + 1} \sum_{r=t-\Delta}^t O(x_r), \quad \mathcal{I}_b(t) = \frac{O(x_t) - O(x_{t-\Delta})}{\Delta + 1}$$

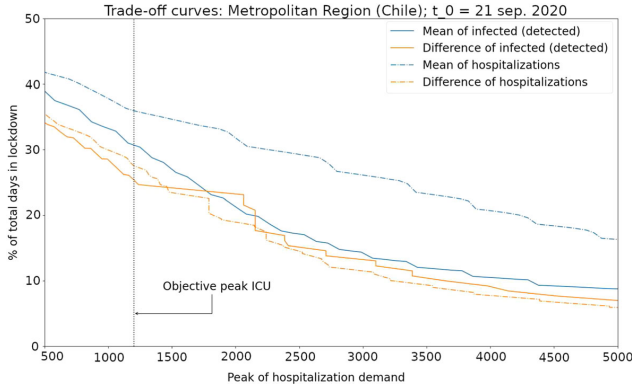


$\Delta = t_{\min} = 14$ days. At least 14 days between switches.

The example ramps intervention strength over 14 days.

Castillo-Laborde et al. (2021)

The threshold traces a curve of policy outcomes



$$P_1 = \max_t H_t^c$$

Peak ICU demand.

$$P_2 = 100 L / (T - t_0)$$

Percentage of time in lockdown, with L the total duration of activated lockdown periods.

Each indicator defines a different curve as θ varies.

Castillo-Laborde et al. (2021). The plot's hospitalisation axis refers to peak ICU demand in this case.

Indicator choice changes lockdown duration

Published simulation result: Metropolitan Region, Chile

Target peak ICU demand: 1,200 beds

Trigger indicator	Threshold θ	Time in lockdown
Mean ICU occupancy	253	36%
Difference in ICU occupancy	8.9	27%
Mean active detected cases	87	31%
Difference in active detected cases	2.2	26%

Similar simulated performance still leaves a question of measurement reliability.

Castillo-Laborde et al. (2021). Historical model assumptions, five-year simulation horizon. Active cases per 100,000 residents. Threshold units follow the indicators on slide 9.

Policy rankings depend on model and observation

What the study establishes

A framework to compare indicators using common intervention rules and explicit outcomes.

Case-specific rankings under calibrated model assumptions.

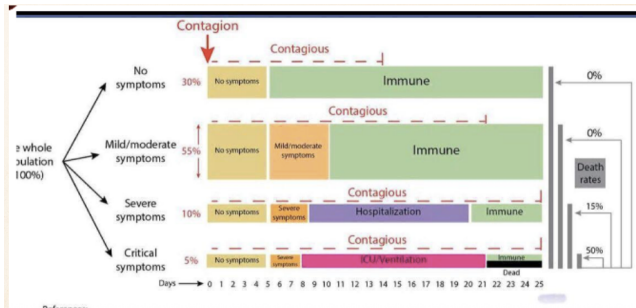
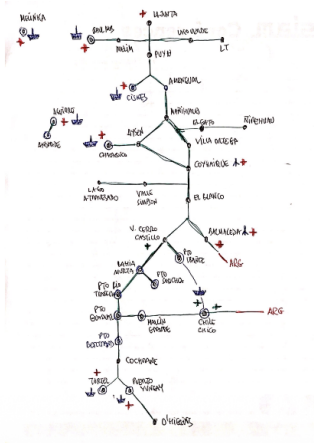
What a new epidemic requires

Reassessment of disease progression, surveillance and contact behaviour.

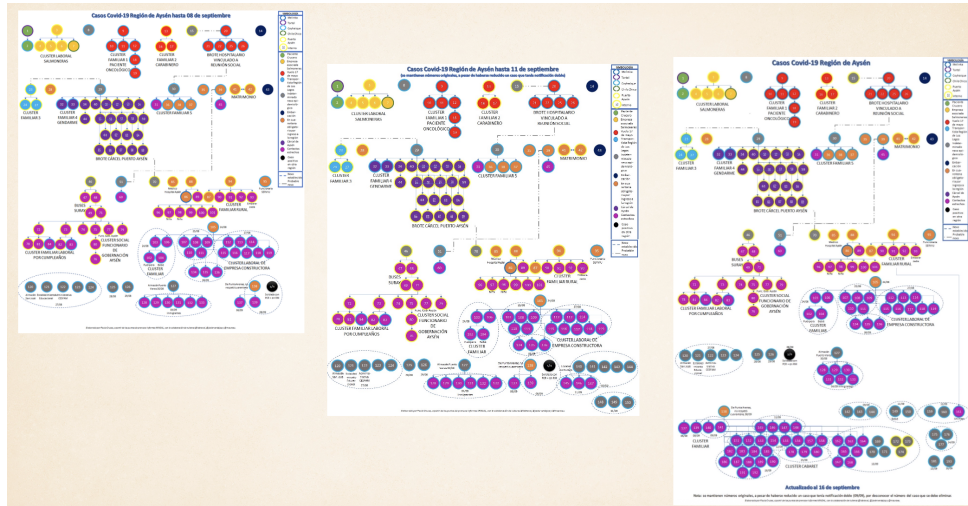
Explicit treatment of changing immunity, treatments and uncertainty.

$$\text{Preferred indicator} = F(\text{model, data, objectives, } x_0)$$

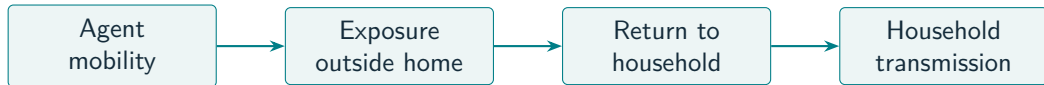
Aysén: 120.000 habitants in 100.000 squared meters



Aysén: 120.000 habitants in 100.000 squared meters



Aysén: a daily cycle of individual exposure



Historical simulator description

60,000 agents and seven zones in the reported setup.

Age and comorbidities appear among the individual attributes.

School and mobility scenarios change where exposures occur.

The household remains part of the transmission process.

An agent model resolves exposure by setting

Illustrative formulation, not a reconstruction of the historical code

$$\lambda_i(t) = \lambda_i^{\text{home}}(t) + \lambda_i^{\text{school}}(t) + \lambda_i^{\text{community}}(t)$$

$$\Pr(S_i \rightarrow E_i \text{ in } [t, t + \Delta t]) = 1 - \exp[-\lambda_i(t)\Delta t]$$

The second expression assumes a constant hazard within the time step.

Interventions modify contacts in each setting. Individual attributes modify susceptibility or clinical progression.

The same average contact reduction can affect different people.

Aysén scenarios illustrate sensitivity to contact structure

Historical scenario	Infections	Peak hospital	Peak ICU	Deaths
Reference	27,826	741	389	293
Schools closed	4,861	130	73	60
50% mobility, schools closed	55	3	1	1
50% mobility, schools open	95	6	3	5
Confinement scenario	12	1	0	0

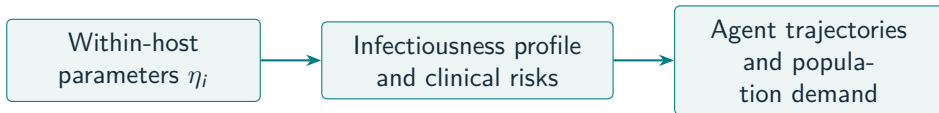
Simulation outputs, not observed effects.

The summary slide does not document uncertainty intervals, replication counts or the simulation horizon.

Biological heterogeneity can enter through distributions

Research extension beyond the two historical studies

$$\eta_i \sim P(\eta \mid \text{age, immune history, comorbidities})$$



Preserve dependencies: susceptibility, infectious duration and severity may be correlated.

Clinical risk requires evidence beyond a viral-load trajectory alone.

Proposed multiscale extension.

Validation across scales

Evidence	Informs	Main ambiguity
Longitudinal viral and immune data	Individual kinetics	Which parameters are identifiable?
Household and contact data	Transmission interface	Biology versus exposure
Cases, admissions and ICU occupancy	Population trajectories	Detection and reporting delays

Proposed checks

Held-out periods or locations. Parameter and structural sensitivity. Repeated stochastic simulations. Policy-rank stability across plausible scenarios.

Validation agenda for a future coupled model.

Future decisions can incorporate uncertainty explicitly

Proposed decision criterion

$$\min_{\pi \in \Pi} \mathbb{E}_{\omega}[L(\pi, \omega)] \quad \text{subject to} \quad \Pr_{\omega} \left(\max_t H_t^c(\pi, \omega) > K \right) \leq \alpha$$

π : indicator-based policy. ω : uncertain scenario and stochastic realization.

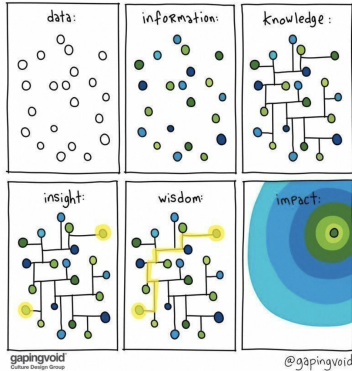
L : intervention duration. K : ICU capacity. α : accepted exceedance probability.

A shared evaluation layer

Compare the same policies with compartmental and agent models. Report capacity risk and intervention burden, including who bears it.

New methodological proposal for discussion.

The biological bridge should earn its decision value



Biology informs distributions of infectiousness and clinical risk.

Contact structure determines who encounters those risks.

Policy evaluation tests whether those details change the decision.

Discussion: Which immune mechanisms would most change the ranking of epidemic interventions?

Sources and acknowledgements

Castillo-Laborde, C., de Wolff, T., Gajardo, P., Lecaros, R., Olivar-Tost, G., and Ramírez C., H. (2021).

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Thank you!



DESCONFINAMIENTO EN AYSÉN

