An economic model of the Covid-19 pandemic with young and old agents: Behavior, testing and policies

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Warwick University, February 2021

Introduction

Covid-19: global pandemic

- age-specific: death rates, behavior, externalities, policy impact
- emphasis on testing (uncertainty about infectious status)
- behavioral change through social distancing even w/o policy

New Version $\rightarrow$ New Results!

- added teleworking
- calibrated to statistical value of life
- computed optimal lockdown

$\rightarrow$ optimal lockdown is quite strict & long and hugely welfare improving

Insights

- we model *behavior*, *incomplete information* & *age*
- benchmark: old shield themselves a lot; young less (death -80%)
- dynamic externality: more careful young *can* lead to more deaths of the old
  $\rightarrow$ but not relevant with vaccine arrival after 1.5 years.

Policy Insights

- optimal lockdown: starts very strict, lasts long (until vaccine), slow easing over time. Cuts deaths by factor 100, welfare improving for all.
- other lockdowns not very effective:
  - strict but short lockdown for all: high welfare costs for the young, few lives saved
  - mild and longer lockdown for all: moderately welfare-improving for all, but also few lives saved
  - lockdown of the old: saves lives but decreases utility of old
- testing works (death -50%)
- testing+quarantines better (up to -100%, young suffice)
- separating activities by age works (death -10%)

Literature

- Greenwood, Kircher, Santos and Tertilt (Econometrica 2019): first quantitative economic model of infectious diseases: adding choice to epidemiology. Context: HIV in Malawi.
- Eichenbaum, Rebelo and Trabandt (COVID): individual behavior, but no age.
- Acemoglu, Chernozhukov, Werning and Whinston (COVID) and Glover, Heathcote, Krueger and Jose-Victor Rios Rull (COVID): age, but no individual behavior.
  $\rightarrow$ matters for interpretation of "policy". Our version: Should we restrict people beyond what they are voluntarily doing? Others: no distinction between government policy vs. individual's protecting themselves.

Model environment

Discrete time

Different ages (a): Young (y) and old (o)

Health status (j):

- healthy (h)
- "fever" (f): unsure whether Covid or common cold
- infected (i): recovery ($\phi(0)$) or serious symptoms (α)
- symptoms (s): recovery ($\phi(1)$) or death (δ_t)
- recovered (r): immune forever

Testing prob ξ_p (p for policy)

Death prob (δ_t): depends on availability of hospital beds

All of the above depend on age a

Vaccine available after 1.5 years

Households

Time: work outside n, telework v, leisure outside ℓ, leisure home d

Time constraint (TC): $n + v + \ell + d = 1$

Leisure goods outside the house g:

$$g(x, \ell) = [\theta x^{\rho} + (1 - \theta)\ell^{\rho}]^{1/\rho}$$

Preferences:

$$u(c, g, d; j, a, p) = \ln c + \gamma \ln g + [\underbrace{\lambda(j) + \lambda_p(j, a)}_{\text{altriusm/policy}}] \ln(d) + b$$

Discount factor (with natural death prob): $\beta(a)$

Wages $w(a, n, v)$: $w[n + \tau(v)v]$ for the young and $\overline{w}$ for the old

Teleworking: $\tau(v) = \tau_0 - \tau_1 v$, BC: $c + x = w(a, n, v)$

Infections

Covid:

$$\pi(n+\ell,\Pi_t(a)) = \underbrace{(n+\ell)}_{\substack{\text{Prob. entering}\\ \text{common space}}} \Pi_t(a)$$

Common cold:

$$\pi^*(n+\ell) = (n+\ell)\Pi^*$$

Covid transmission probability: (vaccine after 1.5 year)

$$\hat{\Pi}_t(a) = \Pi_0 \underbrace{\sum_{a',j\in\{f_i,i,s\}} \big(n_t(j,a')+\ell_t(j,a')\big)\, M_t(j,a')}_{\text{other infected per square meter}}$$

$$\Pi_t(a) = \underbrace{1-e^{-\hat{\Pi}_t(a)}}_{\text{continuous time aggregation}}$$

Also consider selective mixing: some space reserved only for old

Summarizing how age matters in model

- Old do not work $\rightarrow$ spend naturally more time at home.
- COVID19 is more risky for them
    - Higher probability of becoming critically ill.
    - Once critically ill, higher chance of dying.

  $\rightarrow$ Makes them further increase time at home voluntarily.
- Also higher chance of dying from “natural causes.”

Decision making (w/o testing): healthy people

$$
\begin{aligned}
V_t(h,a) = \max_{c,x,n,v,\ell,d} & \, u(c, g(x,\ell), d; h, a, p_t) + \\
& \beta(a)[1 - \pi_f(n+\ell, \Pi_t(a))] V_{t+1}(h,a) + \\
& \beta(a)(a))\pi_f(n+\ell, \Pi_t(a)) V_{t+1}(f,a) \\
& \text{s.t. (TC) and (BC).}
\end{aligned}
$$

Adding Testing

Healthy:

$$
\begin{aligned}
V_t(h,a) = \max_{c,x,n,v,\ell,d} & u(c, g(x,\ell), d; h, a, p_t) + \\
& \beta(a)[1 - \pi_f(n+\ell, \Pi_t(a)) + \pi^*(n+\ell, \Pi_t(a))\xi_{p_t}(a)] V_{t+1}(h,a) + \\
& \beta(a)\xi_{p_t}(a)\pi(n+\ell, \Pi_t(a)) V_{t+1}(i,a) + \\
& \beta(a)(1 - \xi_{p_t}(a))\pi_f(n+\ell, \Pi_t(a)) V_{t+1}(f,a) \\
& \text{s.t. (TC) and (BC).}
\end{aligned}
$$

Decision making

Those known to be infected choose

- time at work, telework, time at home and leisure outside
- consumption and leisure goods

to maximize their life-time utility, taking into account:

- that they want to (somewhat) protect others
- that they may become critically ill
- time constraint
- budget constraint

Decision making

People with a fever choose

- time at work, telework, time at home and leisure outside
- consumption and leisure goods

to maximize their life-time utility, taking into account:

- that they may already have COVID19 (and how likely this is, given the aggregate prevalence rate in that week)
- that if they do have it, they want to (somewhat) protect others
- that if they don't have it, they may catch it
- time constraint
- budget constraint

If tested, they know immediately whether they have COVID19.

Decision making: Severely sick & Recovered

Severely sick

- don't choose anything
- don't work
- may die or recover
- can still infect others

Recovered

- assumed to be immune forever
- back to choosing consumption and time uses

Aggregation

Output: sum of wages

Laws of motion: as you would expect

Death prob: constant unless no hospital bed

Equilibrium

A rational-expectations equilibrium in this economy with initial number of agents $M_0(j,a)$ consists of a sequence of infection and death rates $\{\Pi_t(a), \delta_t(a)\}_{t=0}^{\infty}$ and equilibrium time allocations $\{n_t(j,a), \ell_t(j,a)\}_{t=0}^{\infty}$ such that:

- these time allocations are part of the solutions to the individual optimization problems, and
- the resulting laws of motion and their aggregation indeed give rise to the sequence $\{\Pi_t(a), \delta_t(a)\}_{t=0}^{\infty}$.

Calibration

- Calibrate to US economy
- Model period is a week
- Caveat: uncertainty about the data

Moments: Model vs. Data

Moment	Model	Data (ranges)
Common colds per year	3	2-4
R_0, Covid-19	2.5	1.6-4
% of infected in critical care, young	3.33	3.33
% of infected in critical care, old	9.10	9.10
% in critical care that dies, young	14.2	5-24
% in critical care that dies, old	65.0	40-73
Weeks in critical care, young	3.5	3-6
Weeks in critical care, old	3.5	3-6
Hours/day interacting while in ICU	3.8	7.6 (controlled)
Life expectancy (natural), young	∞	79
Life expectancy (natural), old	20	20

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Moments: Model vs. Data continued

Moment	Model	Data (ranges)
Hours of work per week	40	
Hours of outside activities per week	17.3	17.3
% of income on goods outside	12.5	11.1-16.1
% ↑ in time @ home - mild symptoms	50	50 (H1N1)
Replacement rate - social security, %	60	46-64
% of weekly hours in telework (normal times)	8	8
% ↓ in output w/ 36% of workers in telework	10	10
Value of a statistical life (in million USD)	9.3	9.3

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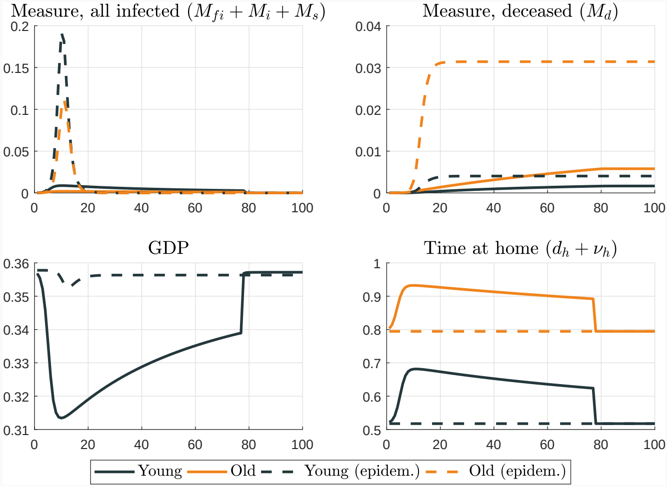
Benchmark results



Benchmark results

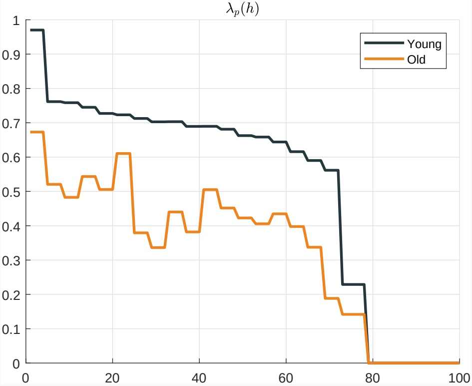
	Benchmark	Epidemiological Model	No disease
Wks to peak srsly ill (yng)	15.00	12.00	
Wks to peak srsly ill (old)	11.00	12.00	
Dead p/ 1,000 1year (yng)	1.22	4.04	
Dead p/ 1,000 1year (old)	4.03	31.40	
Dead p/ 1,000 1year (all)	1.82	9.89	
Dead p/ 1,000 LR (yng)	1.66	4.04	
Dead p/ 1,000 LR (old)	5.79	31.40	
Dead p/ 1,000 LR (all)	2.55	9.89	
Immune in LR (yng), %	35.12	85.29	
Immune in LR (old), %	8.67	45.81	
Immune in LR (all), %	29.46	76.84	
GDP at peak - rel to BM	1.00	1.13	1.14
GDP 1year - rel to BM	1.00	1.09	1.10
Hrs @ home (yng) - peak	76.29	57.97	57.97
Hrs @ home (old) - peak	104.44	88.99	88.99

Voluntary cautious behavior saves many many lives!

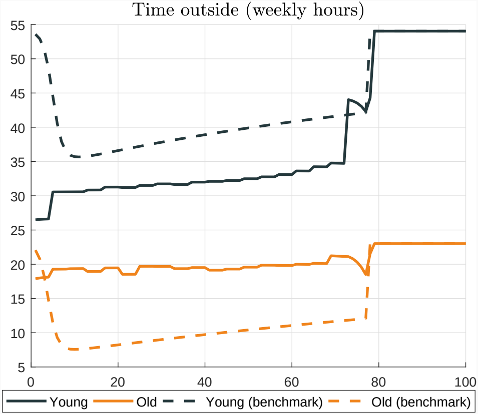
Policy experiments

- Measure "success of a policy" relative to BM with voluntary reductions in time outside.
- The choice of BM is important: Most lockdown policies are hugely welfare improving relative to epidemiological version of the model but much less so relative to BM.
- Distinguishes us from Acemoglu et al and Glover et al.

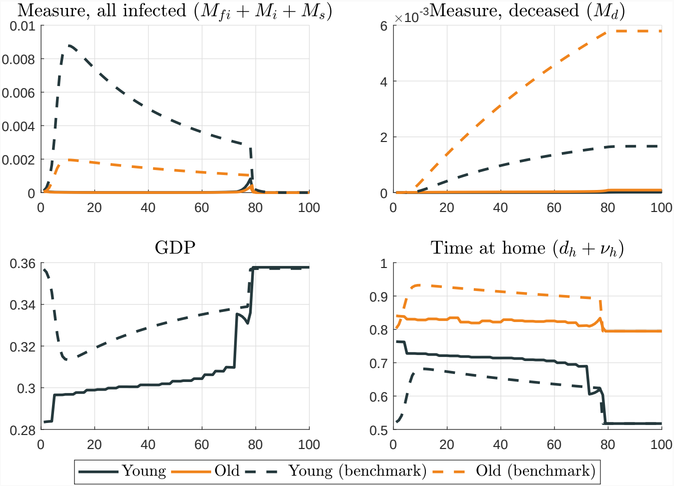
Optimal lockdown policy (in progress)



Optimal lockdown: Weekly Hours Outside



Optimal lockdown policy (in progress)



Optimal vs. other Lockdown Policies

	Benchmark	Optimal Policy	strict & short	mild & longer	strict & long, old only
Wks to peak srsly ill (yng)	15.00	79.00	19	46	15
Wks to peak srsly ill (old)	11.00	79.00	24	43	40
Dead p/ 1,000 LR (yng)	1.66	0.02	1.49	1.24	1.65
Dead p/ 1,000 LR (old)	5.79	0.09	5.09	4.83	3.51
Dead p/ 1,000 LR (all)	2.55	0.03	2.26	2.01	2.05
Immune in LR (yng), %	35.12	0.32	31.5	26.3	34.9
Immune in LR (old), %	8.67	0.14	7.66	7.3	5.3
Immune in LR (all), %	29.46	0.28	2.64	22.2	28.6
GDP at peak - rel to BM	1.00	1.06	0.99	1.02	1.003
GDP 1year - rel to BM	1.00	0.92	0.98	0.97	1.001
Cost p/ life saved, million $	–	2.04	3.19	3.45	none
Value - healthy (yng)	9484.60	9496.00	9481.6	9487.4	9484.7
Value - healthy (old)	4337.20	4372.50	4337.7	4345	4318.9
Value - healthy (all)	8383.00	8399.60	8380.8	8386	8379.2

- May explain why there is so much political debate.
- All policies welfare improving relative to epidemiological model!
- Acemoglu et al argue that lockdown for the old is best policy – We disagree! (Old are a small and careful group with little externality on others, restricting them is either not binding or welfare-decreasing)

Test and Quarantine

	Benchmark	Testing all	Q90-a-50t	Q90-a-100t	Q90-y-100t
Wks to peak srsly ill (yng)	15.00	28.00	25.00	3.00	3.00
Wks to peak srsly ill (old)	11.00	25.00	22.00	3.00	3.00
Dead p/ 1,000 1year (yng)	1.22	0.58	0.46	0.00	0.00
Dead p/ 1,000 1year (old)	4.03	2.33	1.97	0.01	0.01
Dead p/ 1,000 1year (all)	1.82	0.95	0.78	0.00	0.01
Dead p/ 1,000 LR (yng)	1.66	0.84	0.69	0.00	0.00
Dead p/ 1,000 LR (old)	5.79	3.40	2.94	0.01	0.01
Dead p/ 1,000 LR (all)	2.55	1.39	1.17	0.00	0.01
Immune in LR (yng), %	35.12	17.77	14.64	0.05	0.06
Immune in LR (old), %	8.67	5.11	4.42	0.02	0.02
Immune in LR (all), %	29.46	15.06	12.45	0.04	0.05
Max. n. of tests in a week, %	0.00	4.72	2.36	4.76	4.27
GDP at peak - rel to BM	1.00	1.07	1.09	1.14	1.14
GDP 1year - rel to BM	1.00	1.05	1.06	1.10	1.10
GDP gain per test, 1 year, $	–	1431.00	3286.90	2282.60	2540.10
Value - healthy (yng)	9484.60	9494.20	9495.70	9502.70	9502.70
Value - healthy (old)	4337.20	4355.60	4358.70	4373.40	4373.40
Value - healthy (all)	8383.00	8394.50	8396.40	8405.00	8405.00

Summarizing

- Voluntary activity reductions: 80% less deaths, driven by old.
- Lockdowns have many pitfalls (may save only few lives at substantial cost, may hurt the young or the old).
- Optimal lockdown: reduces activity by young, not old! Reduces deaths by factor 100 at sizeable GDP cost (8% decline in first year), but hugely welfare improving.

What else? Testing:

- testing all and no quarantine: 50% less deaths (GDP$\uparrow$ 5%)
- testing 50% and quarantine: 60% less death (GDP$\uparrow$ 6%)
- testing all and quarantine: very few cases (GDP$\uparrow$ 10%)

Robustness

- Hospital bed (ICU) constraints (make lockdown policies even more desirable)
- Without teleworking (lockdowns a lot more costly)
- Later vaccine arrival (in limit, no point of lockdown)

Other caveats

- Uncertainty regarding calibration
- No asymptomatic cases
- Immediate test results

Appendix

Parameters - disease

Parameter	Value	Interpretation
	0.214	Fraction of old in Population
Π^*	0.113	Weekly infectiousness of common cold/flu
Π_0	13.425	Infectiousness of Covid-19
α	1	Prob(serious symptoms | no recovery from mild)
$\phi(0,y)$	0.983	Prob of recovering from mild Covid-19, young
$\phi(0,o)$	0.954	Prob of recovering from mild Covid-19, old
$\phi(1,y)$	0.284	Prob of recovering from serious Covid-19, young
$\phi(1,o)$	0.284	Prob of recovering from serious Covid-19, old
$\bar{\ell}$	0.158	Infections through the health care system
$\delta(y)$	0.065	Weekly death rate (among critically ill), young
$\delta(o)$	0.738	Weekly death rate (among critically ill), old
$\Delta(y)$	1	Weekly survival (natural causes), young
$\Delta(o)$	0.999	Weekly survival (natural causes), old
T^*	78	One and a half year (78 weeks) to vaccine arrival

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Parameters - Economic & Preferences

Parameter	Value	Interpretation
ρ	-1.72	Elasticity of subst. bw leisure time and goods
θ	0.033	Production of leisure goods
γ	0.635	Rel. utility weight - leisure goods
λ_d	1.56	Rel. utility weight - leisure at home
$\lambda(i)$	1.068	Rel. utility weight - leisure at home (infected)
b	11	Flow value of being alive
$\tilde{\beta}$	$0.96^{1/52}$	Discount factor
w	1	Wage per unit of time
τ_0	1.055	Parameter related to telework productivity
τ_1	0.960	Parameter related to telework productivity
$\overline{w}$	0.214	Retirement income

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