# Firm behavior during an epidemic

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Topics in Empirical Analysis and Economic Modeling Related to COVID-19

FGV

# Introduction

- Ongoing COVID-19 epidemic has claimed approx. 4 million lives
- Several economic and health impacts are related to firms
- Various policies targeting firms are being used worldwide
- Employee health is one of the main concerns of firms (Bartik et al., 2020)
- This paper: study labor allocation behavior of firms in an epidemic environment and how that can affect the dynamics of the epidemic

# This paper

Structural model of firm behavior and disease transmission

- Firms
  - Maximizes discounted profits
  - Workers $\rightarrow$ on-site, teleworking, furlhough, sick-leave
  - Infectious workers transmit disease in the workplace
    - Firm internalizes this
- General equilibrium
  - Distribution of workers across health statuses determine aggregate infectiousness
- Calibration: COVID-19 in the U.S.

# Preview of results

- Firm fights infections
    - Teleworking
    - Weekly rotation: on-site work $\leftrightarrow$ telework (two groups)
    - Flattens aggregate infection curve
- Subsidies to sick-leave reduce cost of sick worker $\rightarrow$ more deaths
- Furlough policies and subsidies to teleworking save lives
- Firm delays the fight against infection during economic downturns
- Planner adopts no-COVID strategy if vaccine arrives in 1.5 years

▸ Literature

# Model

- Time is discrete and runs forever
- Continuum of identical firms
- Firms choose allocation of employees
- Workforce of the firm
  - On-site employees (more productive, higher risk)
  - Teleworking (remote) employees (less productive, lower risk)
  - Employees on leave (furloughed)
  - Employees on sick leave
- On-site infectious employees transmit to susceptible on-site employees
- Firm takes workplace transmission into account
- Firm takes infection outside of the workplace as given

# Model

- Production function of firm is

$$f(n,h) = A(n+\gamma h)^{\alpha}, \quad A > 0,\ \alpha,\gamma \in (0,1) \tag{1}$$

  - $n$: mass of on-site workers
  - $h$: mass of teleworkers
- Per-period profit of the firm is

$$\pi(n,h,\ell,s) = f(n,h) - \delta_n wn - \delta_h wh - \delta_\ell w\ell - \delta_s ws \tag{2}$$

  - $\ell$: mass of workers on leave
  - $s$: mass of symptomatic sick workers
  - $\delta$: relative cost/policy parameters
  - $w$: wage, parameter

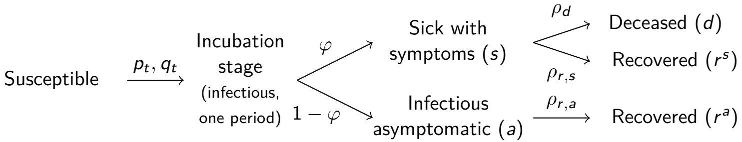
# World before the epidemic

- $N$: number of workers in the no-disease scenario

$$N = \underset{n}{\operatorname{argmax}}\ An^{\alpha} - \delta_n wn \tag{3}$$

- Disease arrives unexpectedly
- No hiring/firing after disease arrives

# Infections and health states




- $q_t$: probability of an employee getting infected if not on-site in $t$
    - Firm takes $\{q_t\}_t$ as given
- $p_t(\mu)$: probability of infection in $t$ if on-site and there are $\mu$ infectious on-site employees
    - Firm internalizes its effect on $p_t$

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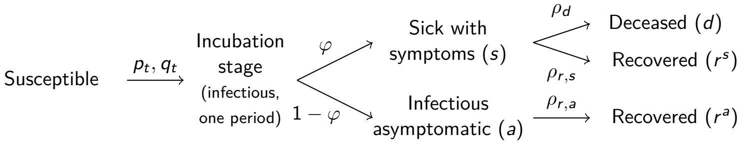


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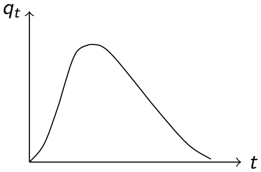

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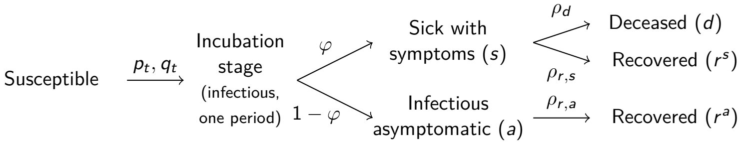


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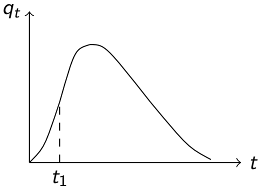

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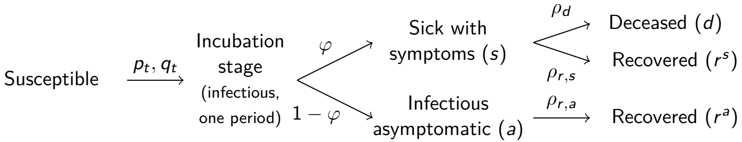


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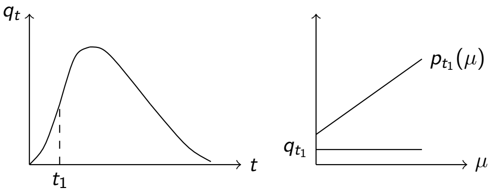

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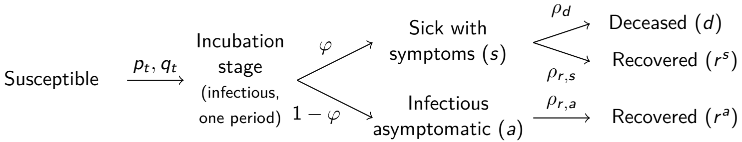


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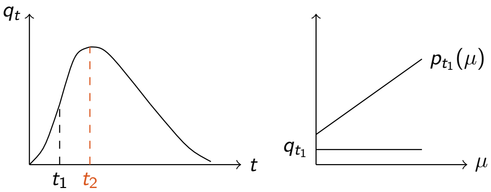

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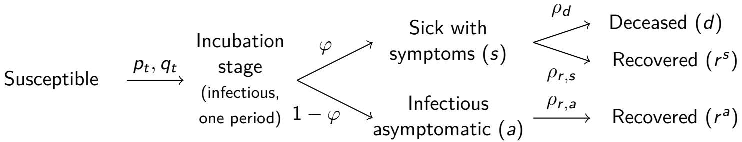


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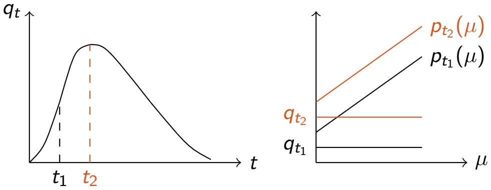

# Human resources by health status

- Firm observes four groups of workers:
  1. Deceased
  2. Sick symptomatic
  3. Recovered symptomatic
  4. Employees with uncertain health status
     - 4.1 Susceptible
     - 4.2 Incubated infection (infectious)
     - 4.3 Infectious asymptomatic
     - 4.4 Recovered asymptomatic

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Which groups can the firm manage?

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# Human resources by health status

- Firm observes four groups of workers:
  1. Deceased
  2. Sick symptomatic
  3. Recovered symptomatic
  4. Employees with uncertain health status $\begin{cases} \text{On-site in } t-1 \\ \text{Not on-site in } t-1 \end{cases}$
     4.1 Susceptible
     4.2 Incubated infection (infectious)
     4.3 Infectious asymptomatic
     4.4 Recovered asymptomatic

Which groups can the firm manage?

# Last ingredients

- Choice variables:

| | | On-site in $t$ | Teleworker in $t$ | Furlhough in $t$ |
|---|---|---|---|---|
| Uncertain status | On-site in $t-1$ | $n_t^n$ | $h_t^n$ | $\ell_t^n$ |
| | Not on-site in $t-1$ | $n_t^m$ | $h_t^m$ | $\ell_t^m$ |
| | Recovered workers | $n_t^r$ | $h_t^r$ | $\ell_t^r$ |

- Firm knows laws of motion of the disease
- Firm uses law of large numbers to know distribution of workers across all health states
- Firm maximizes discounted profits
- Initial condition: $\varepsilon$ mass of workers in incubation stage

▸ All equations

# General equilibrium

- Firm takes as given the path of $q_t$
- $q_t$ is determined in equilibrium by the firms' choices

$$q_t = \Pi_q \left[ \text{n. of workers in incubation stage in } t \right. \\ \left. + \text{ n. of asymptomatic sick workers in } t \right] \tag{4}$$

where $\Pi_q > 0$

▸ Features of the model ▸ Calibration

# Benchmark equilibrium

Figure: The dynamics of the epidemic

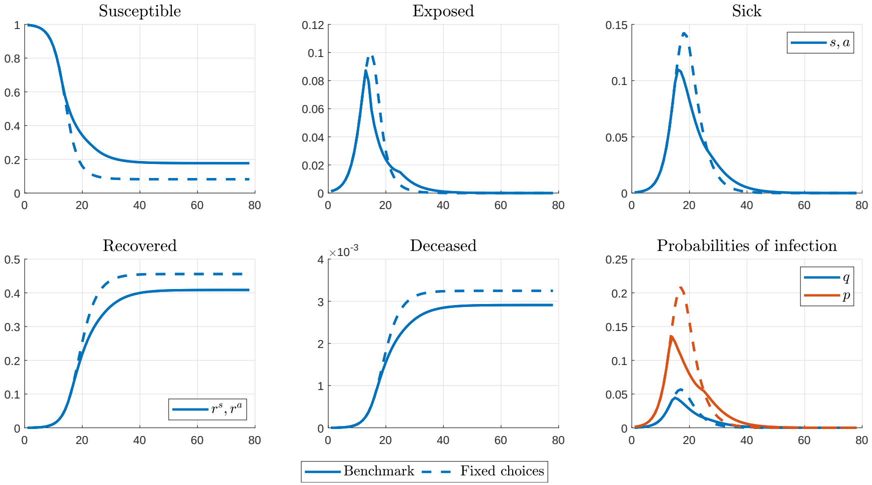
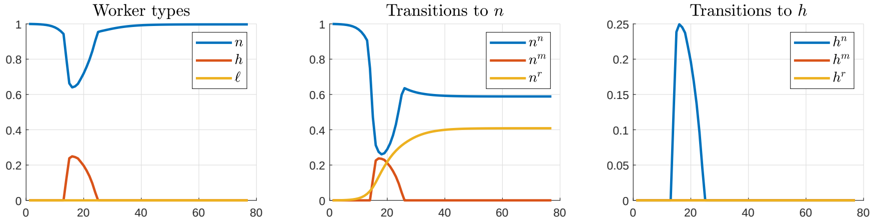


Figure: The dynamics of employee allocations during the epidemic



## Table: Benchmark equilibrium, “epidemiological” model, and policies

| | Benchmark | Fixed choices | Teleworking $\delta_h = 0.975$ | Sick leave $\delta_s = 0$ | Furlough $\delta_\ell = 0$ |
|---|---|---|---|---|---|
| Weeks to the peak | 15 | 17 | 14 | 17 | 16 |
| Sick at the peak (%) | 10.96 | 14.25 | 7.62 | 14.25 | 8.31 |
| Deceased (%) | 0.29 | 0.32 | 0.26 | 0.32 | 0.27 |
| Deceased (%$\Delta$ w.r.t. BM) | 0.00 | 11.54 | -10.01 | 11.54 | -8.27 |
| Recovered (%) | 82.01 | 91.47 | 73.81 | 91.47 | 75.23 |
| Recovered (%$\Delta$ w.r.t. BM) | 0.00 | 11.54 | -10.01 | 11.54 | -8.27 |
| Production 1 year (%$\Delta$ w.r.t. ND) | -2.26 | -2.34 | -2.24 | -2.34 | -7.19 |
| Production 1 year (%$\Delta$ w.r.t. BM) | 0.00 | -0.09 | 0.02 | -0.09 | -5.04 |
| Discounted profits | 381.20 | 381.17 | 381.26 | 382.28 | 381.25 |
| Discounted profits (%$\Delta$ w.r.t. ND) | -0.29 | -0.29 | -0.27 | 0.00 | -0.27 |
| Discounted profits (%$\Delta$ w.r.t. BM) | 0.00 | -0.01 | 0.02 | 0.28 | 0.01 |
| Profits 1 year (%$\Delta$ w.r.t. ND) | -7.11 | -7.32 | -6.59 | -0.11 | -6.77 |
| Profits 1 year (%$\Delta$ w.r.t. BM) | 0.00 | -0.23 | 0.56 | 7.54 | 0.37 |
| Max. teleworking (%) | 24.97 | 0.00 | 32.24 | 0.00 | 17.80 |
| Max. leave (%) | 0.00 | 0.00 | 0.00 | 0.00 | 14.70 |
| Max. $n$ to $m$ (%) | 24.97 | 0.00 | 32.24 | 0.00 | 28.32 |
| Max. $m$ to $n$ (%) | 23.81 | 0.00 | 31.25 | 0.00 | 27.39 |
| Sum $n$ to $m$ | 1.95 | 0.00 | 4.74 | 0.00 | 4.92 |
| Sum $m$ to $n$ | 1.88 | 0.00 | 4.64 | 0.00 | 4.83 |

*Notes:* “BM”: benchmark. “ND”: no-disease.

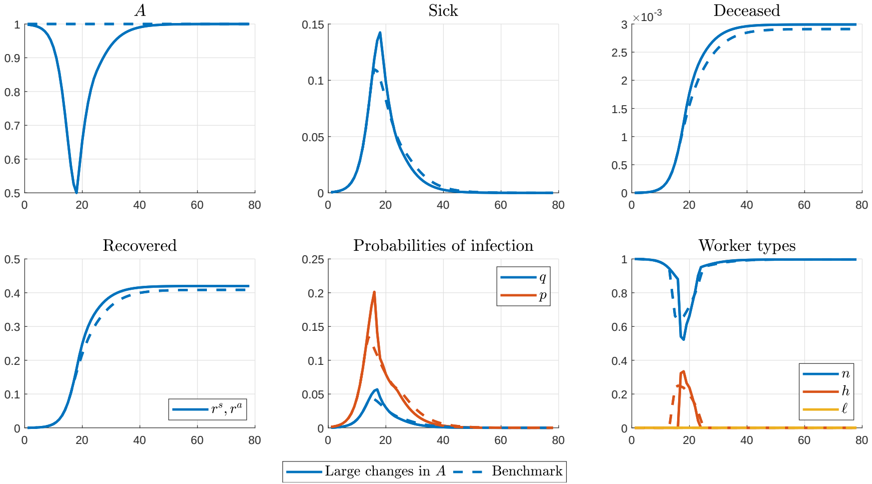
# Production restrictions, changes in the demand, and lockdowns

- Reduced form approach for production restrictions, fall in demand (Fernández-Villaverde and Jones, 2020)
- If more sick individuals, lower demand:

$$A_t = 1 - \delta_A s_t \tag{5}$$

- (Atomistic) firm doesn't internalize this

# Figure: Large changes in $A$



# Firm delays teleworking during the economic downturn. Why?

- Surprising? One expectation could be:

  During downturn, marginal revenue is lower

  $\Rightarrow$ Foregone revenue of teleworker is lower

  $\Rightarrow$ Firm protects workers

- What actually happens:
  - Revenue brought by on-site/teleworker doesn't vary across time:

$$\frac{\text{Mg. rev. of on-site worker in } t}{\text{Mg. rev. of teleworker in } t} = \frac{A_t \times 1}{A_t \times \gamma} = \frac{1}{\gamma} \tag{6}$$

  - Relative costs of different types of workers don't change
  - Opportunity cost of having a sick worker changes over time:

  Foregone revenue of sick worker in $t$ is proportional to $A_t$

# Firm delays teleworking during the economic downturn. Why?

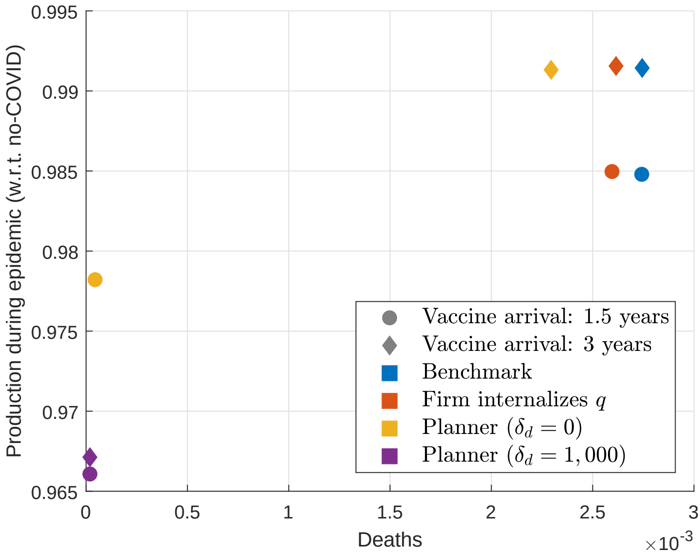
- Opportunity cost of sick worker falls in the COVID outbreak
- Disease is not so deadly for young workers
- Firm wants recovered workers when demand starts moving up
- Firm prefers infections in the beginning rather than in the end
- This aggravates the economic downturn and the infection spike

# A planner

- Planner's objective function:

$$\sum_{t=0}^{\infty} \beta^t \left[ f(n_t, h_t) - \delta_d (d_t - d_{t-1}) \right] \tag{7}$$

- $\delta_d$ captures non-pecuniary value of life
- Planner internalizes the effect of its choices on $q$
- Constrained by laws of motion of the disease



0.995
0.99
0.985
0.98
0.975
0.97
0.965
Production during epidemic (w.r.t. no-COVID)
0
0.5
1
1.5
2
2.5
3
Deaths
$\times 10^{-3}$
Vaccine arrival: 1.5 years
Vaccine arrival: 3 years
Benchmark
Firm internalizes $q$
Planner ($\delta_d = 0$)
Planner ($\delta_d = 1,000$)

# Conclusions

- Novel model where firms operate in an epidemic environment
- Model is calibrated to the COVID-19 in the US
- Firms' choices have significant effects on the epidemic
- Policies can have considerable impacts on the epidemic
- Firms don't fight epidemic in economic downturns
- Planner adopts no-COVID strategy if vaccine arrives in 1.5 years

# References I

Daron Acemoglu, Victor Chernozhukov, Ivan Werning, and Michael D. Whinston. A multi-risk sir model with optimally targeted lockdown. *NBER working paper 27102*, 2020.

Laura Alfaro, Anusha Chari, Andrew N Greenland, and Peter K Schott. Aggregate and firm-level stock returns during pandemics, in real time. Working Paper 26950, National Bureau of Economic Research, April 2020. URL http://www.nber.org/papers/w26950.

Fernando Alvarez, David Argente, and Francesco Lippi. A simple planning problem for covid-19 lockdown. Working paper, 2020.

Alexander W Bartik, Marianne Bertrand, Zoë B Cullen, Edward L Glaeser, Michael Luca, and Christopher T Stanton. How are small businesses adjusting to covid-19? early evidence from a survey. Working Paper 26989, National Bureau of Economic Research, April 2020. URL http://www.nber.org/papers/w26989.

# References II

Luiz Brotherhood, Tiago Cavalcanti, Daniel Da Mata, and Cezar Santos. Slums and pandemics. Unpublished Manuscript, FGV EESP, 2020a.

Luiz Brotherhood, Philipp Kircher, Cezar Santos, and Michèle Tertilt. An Economic Model of the COVID-19 Epidemic: The Importance of Testing and Age-Specific Policies. IZA Discussion Papers 13265, Institute of Labor Economics (IZA), May 2020b. URL https://ideas.repec.org/p/iza/izadps/dp13265.html.

Erik Brynjolfsson, John J Horton, Adam Ozimek, Daniel Rock, Garima Sharma, and Hong-Yi TuYe. Covid-19 and remote work: An early look at us data. Working Paper 27344, National Bureau of Economic Research, June 2020. URL http://www.nber.org/papers/w27344.

CDC. Severe outcomes among patients with coronavirus disease 2019 (covid-19) — united states, february 12–march 16, 2020. *MMWR Morb Mortal Wkly Rep 2020*, 69(12):343–346, 2020.

# References III


CEBM. Covid-19: What proportion are asymptomatic? 2020. URL https://www.cebm.net/covid-19/covid-19-what-proportion-are-asymptomatic/.

Tat Chan, Barton Hamilton, and Nicholas Papageorge. Health, risky behavior and the value of medical innovation for infectious disease. *Review of Economic Studies*, 83(3):1737–1755, 2016.

Frederick Chen, Miaohua Jiang, Scott Rabidoux, and Stephen Robinson. Public avoidance and epidemics: insights from an economic model. *Journal of theoretical biology*, 278(1):107—119, June 2011. ISSN 0022-5193. doi: 10.1016/j.jtbi.2011.03.007. URL https://doi.org/10.1016/j.jtbi.2011.03.007.

Wenzhi Ding, Ross Levine, Chen Lin, and Wensi Xie. Corporate immunity to the covid-19 pandemic. Working Paper 27055, National Bureau of Economic Research, April 2020. URL http://www.nber.org/papers/w27055.

# References IV


Martin S Eichenbaum, Sergio Rebelo, and Mathias Trabandt. The macroeconomics of epidemics. Working Paper 26882, National Bureau of Economic Research, March 2020a. URL http://www.nber.org/papers/w26882.

Martin S Eichenbaum, Sergio Rebelo, and Mathias Trabandt. The macroeconomics of testing and quarantining. Working paper, 2020b.

Rüdiger Fahlenbrach, Kevin Rageth, and René M Stulz. How valuable is financial flexibility when revenue stops? evidence from the covid-19 crisis. Working Paper 27106, National Bureau of Economic Research, May 2020. URL http://www.nber.org/papers/w27106.

Neil Ferguson, Derek Cummings, Christophe Fraser, James Cajka, Philip Cooley, and Samuel Burke. Strategies for mitigating an influenza pandemic. *Nature*, 442:448–52, 08 2006. doi: 10.1038/nature04795.

# References V


Jesús Fernández-Villaverde and Charles I. Jones. Estimating and simulating a sird model of covid-19 for many countries, states, and cities. Unpublished Manuscript, Stanford University, May 2020.

Andrew Glover, Jonathan Heathcote, Dirk Krueger, and Jose-Victor Rios-Rull. Health versus wealth: On the distributional effects of controlling a pandemic. Working paper, 2020.

Jeremy Greenwood, Philipp Kircher, Cezar Santos, and Michèle Tertilt. An equilibrium model of the african hiv/aids epidemic. *Econometrica*, 87(4):1081–1113, July 2019.

Veronica Guerrieri, Guido Lorenzoni, Ludwig Straub, and Ivan Werning. Macroeconomic implications of covid-19: Can negative supply shocks cause demand shortages? Working paper, 2020.

# References VI

Tarek Alexander Hassan, Stephan Hollander, Laurence van Lent, and Ahmed Tahoun. Firm-level exposure to epidemic diseases: Covid-19, sars, and h1n1. Working Paper 26971, National Bureau of Economic Research, April 2020. URL http://www.nber.org/papers/w26971.

Greg Kaplan, Benjamin Moll, and Gianluca Violante. Pandemics according to hank. Working paper, 2020.

Michael Kremer. Integrating behavioral choice into epidemiological models of aids. *The Quarterly Journal of Economics*, 111(2):549–573, 05 1996. ISSN 0033-5533. doi: 10.2307/2946687. URL https://doi.org/10.2307/2946687.

Flavio Toxvaerd. Rational disinhibition and externalities in prevention. *International Economic Review*, 60(4):1737–1755, 1 2019.

# References VII

Robert Verity, Lucy C Okell, Ilaria Dorigatti, Peter Winskill, Charles Whittaker, Natsuko Imai, Gina Cuomo-Dannenburg, Hayley Thompson, Patrick GT Walker, Han Fu, et al. Estimates of the severity of coronavirus disease 2019: a model-based analysis. *The Lancet Infectious Diseases*, 2020.

# Appendix

# Literature

## Pre-COVID

- Theory
  - Kremer (1996), Chen et al. (2011), Toxvaerd (2019)
  - Infected agents impose negative externalities on susceptible by not internalizing the costs of transmission
- Quantitative
  - Chan et al. (2016), Greenwood et al. (2019)
  - The role of this externality in quantitative economic models of disease transmission
- Our contribution
  - Firms internalize some of these externalities...
  - ... with a different objective function (profits)

# Literature

## Post-COVID

- Structural models with COVID-19 transmission:
  - Alvarez et al. (2020), Acemoglu et al. (2020), Brotherhood et al. (2020a,b), Eichenbaum et al. (2020a,b), Glover et al. (2020), Guerrieri et al. (2020), Kaplan et al. (2020), and others
    - Optimal containment policies, importance of behavior, testing, macroeconomic stabilization policies...
    - Common aspect of all: focus on modeling workers
    - Our contribution: first paper modeling firms in an environment with disease transmission
- Empirical papers assessing impacts on firms:
  - Alfaro et al. (2020), Bartik et al. (2020), Ding et al. (2020), Fahlenbrach et al. (2020), Hassan et al. (2020)

Back

# Laws of motion

$$d_{t+1} = d_t + \rho_d s_t \tag{8}$$

$$r^s_{t+1} = r^s_t + (1-\rho_d)\rho_{r,s} s_t \tag{9}$$

$$r^a_{t+1} = r^a_t + \rho_{r,a} a_t \tag{10}$$

$$s_{t+1} = (1-\rho_d)(1-\rho_{r,s}) s_t + \varphi(\tilde{n}_t + \tilde{m}_t) \tag{11}$$

$$a_{t+1} = (1-\rho_{r,a}) a_t + (1-\varphi)(\tilde{n}_t + \tilde{m}_t) \tag{12}$$

- $\tilde{n}_t$: on-site employees with incubated infection in $t$
- $\tilde{m}_t$: out of workplace employees with incubated infection in $t$

- $a_{n,t}$: on-site asymptomatic employees (infectious) in $t$

$$a_{n,t} = (n_t^n + n_t^m)\frac{a_t}{N - r_t^s - s_t - d_t} \tag{13}$$

- Probability of infection of on-site employees

$$p_t = \min\{\Pi_{p,q} q_t + \Pi_{p,n}(\tilde{n}_t + a_{n,t}), 1\} \tag{14}$$

where $\Pi_{p,q} \geq 1$ and $\Pi_{p,n} > 0$

- $c_{t-1}$: fraction of susceptible among uncertain workers in $t-1$

$$c_{t-1} = 1 - \frac{r_t^a + a_t}{N - r_t^s - s_t - d_t} \tag{15}$$

- Laws of motion for $\tilde{n}_t$ and $\tilde{m}_t$

$$\tilde{n}_t = n_t^n c_{t-1} p_{t-1} + n_t^m c_{t-1} q_{t-1} \tag{16}$$

$$\tilde{m}_t = (h_t^n + \ell_t^n) c_{t-1} p_{t-1} + (h_t^m + \ell_t^m) c_{t-1} q_{t-1} \tag{17}$$

# Constraints

- Workers in each group must be split among available options:

$$n_t^n + h_t^n + \ell_t^n = n_{t-1}^n + n_{t-1}^m - \varphi \tilde{n}_{t-1} \tag{18}$$

$$n_t^m + h_t^m + \ell_t^m = h_{t-1}^n + \ell_{t-1}^n + h_{t-1}^m + \ell_{t-1}^m - \varphi \tilde{m}_{t-1} \tag{19}$$

$$n_t^r + h_t^r + \ell_t^r = r_t^s \tag{20}$$

- Initial conditions:

$$n_{-1}^n = N, \quad \tilde{n}_{-1} = \varepsilon \tag{21}$$

all else zero

- $\varepsilon$: initial mass of infected workers

# Firm's problem

- Firm maximizes

$$\sum_{t=0}^{\infty} \beta^t \pi_t \tag{22}$$

  subject to constraints and laws of motion

- Choice variables:

$$n_t^n, h_t^n, \ell_t^n, n_t^m, h_t^m, \ell_t^m, n_t^r, h_t^r, \ell_t^r \geq 0 \quad \forall t \tag{23}$$

# Two-stage problem

- All dynamic equations that depend on $h$ and $\ell$ only depend on these variables through $h + \ell \equiv m$.
- Static problem: for a given $n$ and $m$,

$$\max_{h,\ell \geq 0} A(n + \gamma h)^{\alpha} - \delta_n wn - \delta_h wh - \delta_\ell w\ell - \delta_s ws \tag{24}$$

$$\text{subject to } h + \ell = m \tag{25}$$

- Choice variables of dynamic problem:

$$n_t^n, m_t^n, n_t^m, m_t^m, n_t^r, m_t^r \geq 0 \quad \forall t \tag{26}$$

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# Features of the model

- The epidemic has negatives effects on output and profits
  - Workforce shrinks: employees catch infection and take a sick leave
  - Fall in output and profits since $\delta_s > 0$ and the firm cannot achieve its optimal size
  - Workforce is smaller after the culmination of the epidemic because of fatalities
  - This also reduces output and profits
- All known recovered employees are allocated on-site
- Decreasing returns to scale technology
  - Firm wants to smooth infections over time

# Features of the model

- Firm wants to allocate employees into teleworking and leave in times of an epidemic
  - These reduce $p_t$ and infections among all employees given that $p_t \geq q_t$
- Dynamic trade-offs:
  - On-site workers:
    - Higher output in the present and in the "distant" future
    - Sick-leave, fatality
  - Teleworking employees:
    - Lower productivity
    - Lower infection probability
- Incentives to rotate employees between on-site work and teleworking
  - On-site worker in $t-1$ has higher probability of being infectious in $t$

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# Calibration

| Parameter | Value | Comment |
|---|---|---|
| **Panel A. Firm** | | |
| $A$ | 1 | Normalization |
| $N$ | 1 | Normalization |
| $\alpha$ | 0.7 | Labor share of revenues |
| $\beta$ | $0.96^{1/52}$ | Time discount (weekly) |
| $\gamma$ | 0.935 | $\approx$ 30% in teleworking at peak (Brynjolfsson et al., 2020) |
| $w$ | 0.7 | Wage is such that optimal $N = 1$ in no disease/epidemic times |
| $\delta_n, \delta_h, \delta_\ell, \delta_s$ | 1 | Policy parameters |
| **Panel B. COVID-19** | | |
| $\rho_{r,s}$ | 1/3.52 | Average duration of hospitalization (Verity et al., 2020) |
| $\rho_{r,a}$ | 1/3.52 | Same as $\rho_{r,s}$ |
| $\rho_d$ | 0.00202 | Probability of death conditional on hospitalization (CDC, 2020) |
| $\Pi_q$ | 0.25 | $R_0 = 2.5$ |
| $\Pi_{p,q}$ | 1 | No discontinuity from $q$ to $p$ |
| $\Pi_{p,n}$ | 0.6667 | $\approx$ 50% transmissions in the workplace at peak (Ferguson et al., 2006) |
| $\varphi$ | 0.5 | Proportion of asymptomatic, range: 4%-75% (CEBM, 2020) |
| $\varepsilon$ | 0.001 | 0.1% infected workers in first period |
| **Panel C. Time** | | |
| Time period | 1 week | |
| Epidemic end | 1.5 years | Deterministic vaccine arrival |

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