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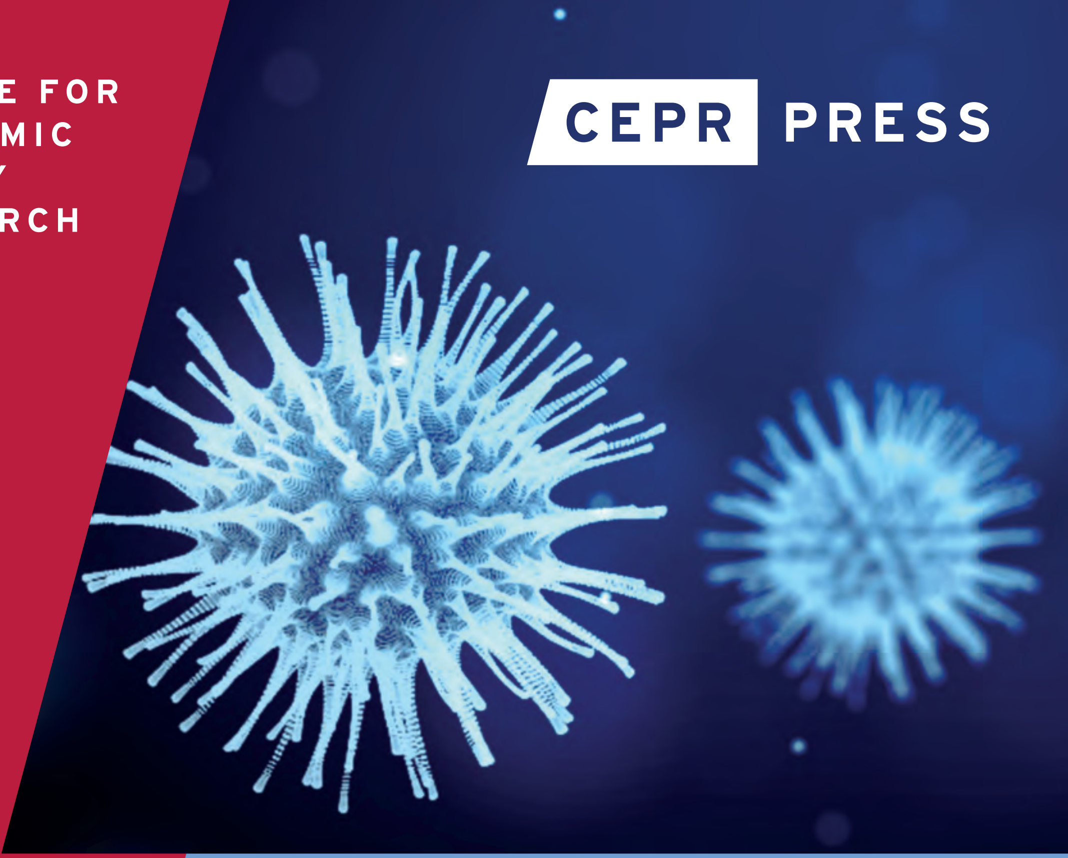

COVID ECONOMICS

VETTED AND REAL-TIME PAPERS

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Covid Economics
Vetted and Real-Time Papers

Covid Economics, Vetted and Real-Time Papers, from CEPR, brings together formal investigations on the economic issues emanating from the Covid outbreak, based on explicit theory and/or empirical evidence, to improve the knowledge base.

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Contact: Submissions should be made at https://portal.cepr.org/call-papers-covid-economics. Other queries should be sent to covidecon@cepr.org.

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Ethics

Covid Economics will feature high quality analyses of economic aspects of the health crisis. However, the pandemic also raises a number of complex ethical issues. Economists tend to think about trade-offs, in this case lives vs. costs, patient selection at a time of scarcity, and more. In the spirit of academic freedom, neither the Editors of *Covid Economics* nor CEPR take a stand on these issues and therefore do not bear any responsibility for views expressed in the articles.

Submission to professional journals

The following journals have indicated that they will accept submissions of papers featured in *Covid Economics* because they are working papers. Most expect revised versions. This list will be updated regularly.

American Economic Review

American Economic Review, Applied Economics

American Economic Review, Insights

American Economic Review, Economic Policy

American Economic Review, Macroeconomics

American Economic Review, Microeconomics

American Journal of Health Economics

Canadian Journal of Economics

Economic Journal

Economics of Disasters and Climate Change

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Journal of Economic Growth

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Journal of Public Economics

Journal of Political Economy

Journal of Population Economics

*Quarterly Journal of Economics**

Review of Economics and Statistics

*Review of Economic Studies**

Review of Financial Studies

(*) Must be a significantly revised and extended version of the paper featured in *Covid Economics*.

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Six degrees of separation for Covid-19: The external costs and benefits of extended distancing for different social groups

Carolyn Fischer[1]

Date submitted: 29 May 2020; **Date accepted:** 30 May 2020

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After an initial period of crisis management, governments must consider what measures against the spread of the novel coronavirus to keep in place until a vaccine or reliable therapy arrives. Informing public policy requires understanding not only disease dynamics and social distancing effectiveness, but also economic features to evaluate the costs and benefits of different actions. This study adapts a workhorse epidemiological model to account for both age-dependent risks and job-dependent social distancing measures and costs. Simulations calculate the costs of six different degrees of restrictions, with sensitivity analysis to several uncertain underlying disease parameters. A novel contribution is contrasting private cost-benefit calculations with the external costs and benefits to society as a whole. The least-cost policy likely involves continued isolation of all who can work or study at home, while other workers practice strong social distancing. For the US, this strategy saves on the order of $10 trillion as compared to simply isolating vulnerable individuals. The benefits of requiring other workers to stay at home only outweigh the wage losses if social distancing measures are insufficiently effective. Immunity is a critical parameter and its absence dramatically increases the costs of weak actions. Further research into the

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nonmonetary costs of isolation would be valuable. The value of the risks a single person can impose on the rest of society by not staying at home can be substantial, generally increases as restrictions loosen, and should be weighed against the private benefits of returning to circulation.

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Six Degrees of Separation for COVID-19:

The External Costs and Benefits of Extended Distancing for Different Social Groups

1. Introduction

Governments around the world are wrestling with what restrictions to impose on daily life in order to manage public health during the novel coronavirus (SARS-CoV-2, the virus that leads to the disease now named COVID-19) pandemic. Policies range from extreme lockdowns on all but essential work in Wuhan, China, and Italy to softer recommendations in Sweden that all who can work from home do so and that people who go out in public practice social distancing—wearing masks, avoiding large gatherings, and remaining two meters apart. Now, many jurisdictions are considering relaxing their measures to allow more portions of the population to circulate while still restricting interaction with vulnerable populations, and individuals are deciding to what extent to abide by restrictions or take advantage of openings.

These decisions carry enormous health and economic consequences, as well as stir political controversy. The fields of public, environmental and resource economics are particularly well suited to inform this debate because cost-benefit analysis, dynamic models, and understanding the external effects of private behavior are their stock in trade. Thunström et al. (2020) offered an initial cost-benefit analysis of strict policies to "flatten the curve" in the United States, finding net benefits on the order of $5 trillion.[2] Presciently, Fenichel (2013) emphasized the importance of considering how policies interact with individuals' microeconomic incentives, given that social distancing behavior is often a function of health status. In other words, it is important not only to consider total social costs, but also to contrast the private and public effects of individual behavior.

The high-profile epidemiological models tend to focus on the short term and vary greatly in their forecasts.[3] This range reflects ongoing uncertainty about underlying disease parameters,

[2] Several macroeconomists are also contributing interesting evaluations with different features, as noted subsequently.

[3] The CDC maintains an overview of models at https://www.cdc.gov/coronavirus/2019-ncov/covid-data/forecasting-us.html (updated version accessed May 6, 2020).

policy effects, and behavior in social distancing, despite a rapidly growing array of innovative research.[4] Although many studies still focus on the population as a whole,[5] a growing number consider age-dependent effects and interventions to flatten the curve.[6] However, these models lack some important policy-relevant features for evaluating economic damage beyond the value of lives lost, especially if policies affect different groups in society differently and must be kept in place for a long time—and even with a streamlined process of research, trials, and approvals, a vaccine or reliable therapy is likely at least one to two years away.

This study adapts the workhorse epidemiological model to account for both health and economic effects on different categories of society in a straightforward way. In addition to age-dependent risks, it includes job-dependent social distancing measures and costs. We consider and quantify a broad range of policy responses and conduct sensitivity analysis to several uncertain parameters.[7] The simulations calculate not only the cost-effectiveness of different degrees of restrictions, but also the value of improving the effectiveness of social distancing measures. Finally, we contrast the private cost-benefit calculations with the external costs and benefits to society as a whole. The value of the risks a single worker can impose on the rest of society by not staying at home can be substantial, generally increases as restrictions loosen, and should be weighed against the private benefits of returning to circulation.

2. Model

The conventional SIRD model tracks a population as Susceptible, Infected, Recovered, or Dead. This paper extends the SIRD model to represent multiple categories of people with different behaviors and risks. We make the following assumptions:

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[4] For example, Dandekar and Barbastathis (2020) use neural networks to estimate the effects of policy styles from different countries and forecast an overall spread of infection in the United States.

[5] For example, Eichenbaum et al. (2020) and Krueger et al. (2020) consider aggregate consumption-contagion trade-offs.

[6] See, for example, Matrajt and Leung (2020) on temporary interventions, and Acemoglu et al. (2020) and Gollier (2020) on optimal lockdown shares and welfare impacts.

[7] Pindyck (2020) offers a nice explainer of the influence of disease dynamics in the general population and outcomes relevant for welfare.

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$$
\begin{aligned}
\dot{S}_i &= -S_i(t) \sum_{j\in\{v,w,h\}} \beta_{ij} I_j(t) + \phi R_i(t) \\
\dot{I}_i &= -\dot{S}_i - \dot{R}_i - \dot{D}_i \\
\dot{R}_i &= \gamma I_i(t) - \phi R_i(t) \\
\dot{D}_i &= \gamma \frac{\rho_i}{1-\rho_i} I_i(t)
\end{aligned}
$$

where β_{ij} is the joint rate of contact and infection (CI) between persons of group *i* and *j*[8]; γ is the recovery rate of infected individuals; ϕ is the probability a recovered individual will become susceptible again; and ρ_i is the per capita probability of dying from the infection for type *i*. The mortality rate reflects the probability of dying before recovering $(m_i = \gamma_i \rho_i / (1-\rho_i))$.[9] Furthermore, let $\rho_i = (1-\alpha) CFR_i$, where *CFR* is the category-specific case fatality rate, and α is the rate of mild or asymptomatic illness. Note that deaths from natural causes, as well as entry or transitions into different categories, are ignored.

3. Scenarios

This modified SIRD model is programmed in Mathematica[10] and parameterized for the population of the United States, distinguishing among six different categories of people:

v = vulnerable person at higher risk of mortality from the disease (e.g., older or with pre-existing conditions);

e = essential worker who must remain in circulation (e.g., working in healthcare, food distribution, utilities, etc.);

w = non-essential worker who cannot work at home (“outside worker”);

h = adult person who can work from home or otherwise stays at home;

k = adolescent “kid” (secondary school age);

c = child under 15 (primary or middle school and younger).

Consider the following stylized scenarios, ordered from least to most stringent:

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[8] The CI rate is the joint probability that two individuals will meet and that the contact will result in spreading the virus to the susceptible individual.

[9] Keeling and Rohani (2007, 34).

[10] Code available upon request.

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- **No policy (NP),** normal behavior as before the pandemic;
- **Vulnerable isolation (VI),** isolation of vulnerable individuals, but the remaining population continues in circulation as before the pandemic;
- **Vulnerable distancing (VD),** like VI, but the population in circulation practices social distancing;
- **Simple distancing (SD),** vulnerable individuals and those for whom it is easy to stay or work at home are isolated, while all other workers and primary school children remain in circulation but practice social distancing;
- **Work while distancing (WD),** like SD, but all children stay home; and
- **Lockdown (LD),** all but essential workers are in isolation.

4. Calibration

Epidemiological parameters. The share of infected persons who develop symptoms is important both for tallying mortality and the economic burden of illness. Evidence indicates that 50% to 90% of people infected with the virus remain asymptomatic or suffer only mild effects;[11] we assume 80% in the benchmark,[12] and a 50% asymptomatic rate is considered in sensitivity analysis. Conditional on having symptoms, vulnerable populations have exhibited mortality rates from COVID-19 that are much higher than the relatively low average. Based on early evidence, when cases consisted almost exclusively of symptomatic people, we calculate case fatality rates (CFR) that vary by orders of magnitude for our age groups: 10% for vulnerable individuals, 1% for other adults, 0.1% for adolescents, and 0.01% for young children.[13] Following infection, the recovery rate is assumed to be $\gamma_i = 1/R_{days}$, where $R_{days} = 14$ is the average infectious period and length of time to recover, as well as typical guidelines for self-isolation.[14] Evidence about immunity following recovery is still lacking; the benchmark

[11] Day (2020a,b), Goffman and Sutton (2020) and others cited in Panovska-Griffiths (2020).

[12] Similar to Matrajt and Leung (2020).

[13] Data on cases and fatalities by age group from Onder et al. (2020) for China and Italy and from CDC (2020) for the United States were combined in own calculations.

[14] Studies show that patients are infectious before they show symptoms and especially in the first week after symptoms start (Wölfel et al. 2020). "The incubation period for COVID-19, which is the time

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assumes immunity is conferred for the duration of our time horizon ($\phi = 0$), though in sensitivity analysis we consider a 50 percent rate of returning from recovered to susceptible within six months[15] as well as the possibility of no immunity ($\phi = 1$). We assume 1% of the population is initially infected, equally distributed across categories.

Contact and infection (CI) rates within and between groups are assumed to follow $\beta_{ij} = \sqrt{\beta_i \beta_j}$, where group-specific β_i depends on the policy and parameter scenarios.[16] (See Table A-1 in the Appendix.) We assume that under initial circumstances, $\beta_i = 0.3$ for all *i* in the benchmark parameterization. An important area of uncertainty is the role of children as vectors for the disease; Bi et al. (2020) found children were as likely to be infected as adults, which is retained as the benchmark assumption, but RIVM (2020) indicates children are less likely to transmit SARS-COV-2, so sensitivity analysis considers if children are 50% as infectious. Under initial circumstances, the benchmark assumptions produce a basic reproduction rate of 4.2,[17] a case fatality rate of 3%, and a death rate per infected person of 0.6%. The effectiveness of restrictions on the relevant CI parameters is still under study (see, e.g. Castex et al. 2020); our benchmark assumes that social distancing measures reduce the CI rate by 50%,[18] and isolation by 90% for non-vulnerable people and 95% for vulnerable ones. In sensitivity analysis, we consider more or less effective social distancing measures, particularly for those not staying at home. (Table A-2 in the Appendix summarizes specific parameter values by scenario.)

Population parameters. According to the US Census, the current (2019) population is 324 million, of whom 77.3% are adults. Our vulnerable population is proxied by the 68 million receiving Social Security benefits for retirement or disability. According to the Bureau of Labor

between exposure to the virus (becoming infected) and symptom onset, is on average 5-6 days, however can be up to 14 days" (WHO 2020).

15 This case implies a daily rate of return from recovered to susceptible of $\phi = 1 - 0.5^{1/(26 \cdot 7)} = .0038$.

16 Manski and Molinari (2020) note the statistical challenges in inferring infectiousness; hence we conduct a range of sensitivity analyses.

17 I.e., an average infected individual would be expected to infect another 4 people in a completely susceptible population. This "R_0" is higher than early studies like Riou and Althaus (2020) (1.4–3.8), but within the low end of the range found recently by Sanche et al. (2020) (3.8–8.9).

18 Thunstrom et al. (2020) find that social distancing measures sufficient to decrease the average contact rate among individuals by 38% can reduce the peak of the infection curve by more than half.

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Statistics (BLS), 63% of the adult population is in the labor force. In a recent survey, 29% of workers surveyed reported that they could work from home.[19] The benchmark assumes this number, although Dingel and Neiman (2020) calculate as many as 37% of US jobs can plausibly be performed at home.[20] A recent study of BLS data found that 34% to 43% of jobs could be considered essential (Tomer and Kane 2020); we use the average. The small population of those neither in the labor force nor categorized as vulnerable are assumed able to stay at home. That leaves 32% of workers as nonessential outside workers; although such jobs may not be evenly distributed across household members, the share is broadly consistent with recent Census findings that 47% of households lost earnings during the pandemic (Callen 2020). Table 1 summarizes the resulting distributions from the population data.

Table 1. Distribution of Population, by Group, and Percentage of Population in Circulation, by Policy Scenario

Category:	*v*	*h*	*e*	*w*	*k*	*c*
Population distribution	27%	15%	19%	16%	4%	19%
Scenario:	**NP**	**VI**	**VD**	**SD**	**WD**	**LD**
Population in circulation as normal	100%	73%	0%	0%	0%	0%
Population in circulation but distancing	0%	0%	73%	54%	35%	19%
Population locked down	0%	27%	27%	46%	65%	81%

Economic parameters. Economic effects are calculated in a bottom-up way, applying average values to quantity outcomes from the epidemiological model. This structure allows for transparent calculation of marginal external effects and of first-order effects for total costs.[21] Wage losses for outside workers is our metric for the social cost of lost work, comprising either private costs or public ones (e.g., unemployment benefits). Data from the aforementioned BLS survey indicate that workers who cannot work from home earn roughly $1000 per week, as compared to $1500 for those who can. We assume that those who can stay at home easily do not suffer a wage loss by doing so. An interesting question is the cost of keeping children at home. Bayham et al.

[19] https://www.bls.gov/news.release/flex2.t01.htm.

[20] Hatayama et al. (2020) explore this question internationally using survey data from 53 countries.

[21] By contrast, Thunstrom et al. (2020) use third-party GDP forecasts. Macro models allow for equilibrium feedback effects but are “black boxes” that are hard to scrutinize.

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(2017) estimate the cost of school closures to be about $500 per week per household; although the scenario is not completely analogous, this value is at least indicative of the potential scope.[22] Since the Census indicates that households with children have on average nearly 2 children at home, we use an average cost of $250 per week per child out of school. Our central value for the value of statistical life (VSL) is $10 million, a common (if controversial) estimate that is uniform across all groups.[23] The societal burden of illness for symptomatic patients is proxied by the median cost of COVID-19 treatment, $4000 (Lee 2020), as well as the cost of uncompensated sick leave, which BLS indicates affects 24% of workers. Furthermore, 12.5% of the working-age population is without health insurance, potentially exposing them to uncovered medical expenses, which are included in private cost calculations.[24] We consider a duration of 18 months, at which point a vaccine or effective treatment is assumed to allow restrictions to end, with no time discounting.

5. Results

The epidemiological model shows that even policies primarily targeting vulnerable people are effective at flattening the infection curve. However, keeping a larger share of the population home through progressively stringent restrictions dramatically reduces mortality. Figure 1 displays the symptomatic infection $((1-\alpha)I_i)$ and cumulative mortality (D_i) curves for the different scenarios. A distinction is made between vulnerable persons (in red), nonvulnerable $(-v_i)$ or essential workers (in black), and home workers (in gray).[25] Note that the y-axis in each subsequent row is smaller by a factor of 5.

[22] They base the economic costs of school closures on activity patterns derived from the American Time-Use Survey (ATUS). The duration of shutdown considered was three weeks, and the parents were obviously not otherwise required to be at home. It is not clear whether this would be an over- or under-estimate of long-term distance learning, which could require different time use by parents, different needs for child care, and also lost educational attainment.

[23] For more information about VSL assumptions, see https://www.epa.gov/environmental-economics/mortality-risk-valuation#whatvalue (accessed 5/11/2020). Balmford et al. (2019) find that VSL values for preventing child fatalities significantly exceed those for adults; however, child deaths from COVID-19 are sufficiently rare that this aspect of the uniformity assumption is unlikely to change results.

[24] An additional 6.6% of minors and 1% of over-65s in the US lack health insurance; however, our private cost calculations will focus on workers.

[25] The curves for nonessential outside workers and children will correspond to those of either essential or home workers, depending on the scenario.

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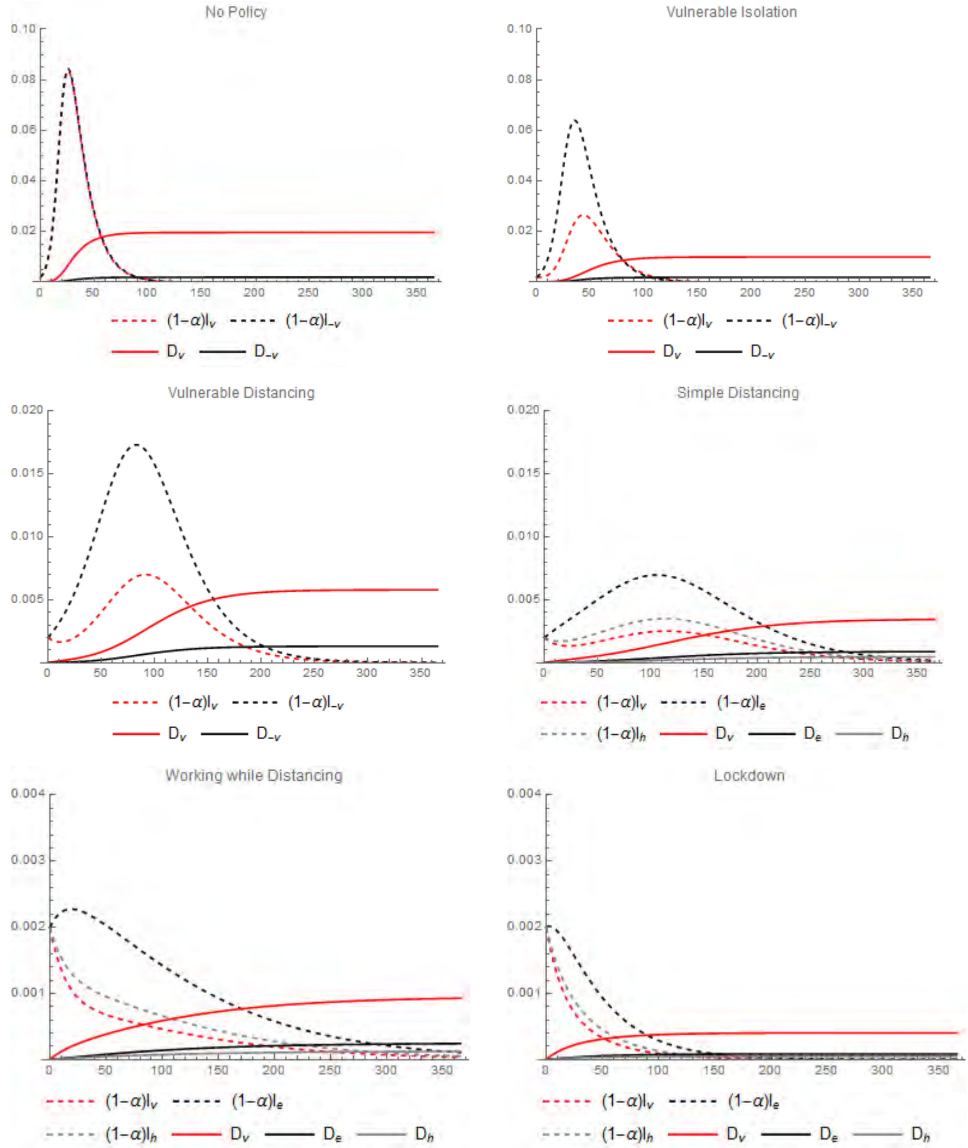
Figure 1. Symptomatic Infection and Mortality Rate, by Group and Policy Scenario (Benchmark Parameterization)



With NP, there is little difference in infection, with symptomatic cases peaking at over 8% of the population, but vulnerable persons have a much higher death rate. With VI, the peak for vulnerable persons is flattened to just over 2%, and the peak for nonvulnerable persons remains just over 6%. With VD, their peak is also flattened to just under 2%. With SD, all outside workers are in circulation, leaving their risk higher than those staying at home. Notably, however, their risk of infection and death is much smaller than if those who could easily stay at home did not do so. Finally, having only essential workers in circulation further reduces risks for all parties. Thus, each group that adopts more restrictive measures contributes not only to their own safety but also to that of others (i.e., providing external benefits).

A trade-off is that slowing the course of the virus with stricter policies leaves a larger share of the population susceptible at the end of the period, motivating the need for policy measures to stay in place until the arrival of a vaccine or therapy.[26] Although only 2% remain uninfected with NP and 17% with VI (herd immunity strategies), 42% remain susceptible under VD, 67% under SD, and over 90% for WD and LD.

Table 2 presents the results for the affected populations and social costs of the different scenarios. The numbers should not be viewed as overly precise—although plausible, the parameter values are uncertain and arguably incomplete.[27] What is telling are the relative magnitudes. With looser policies, the value of lives lost dominates, whereas with stricter policies, the value of lost wages and school closings becomes substantial. The cost of illness is two orders of magnitude smaller, and thus a much smaller part of the story. (Table A-3 in the Appendix gives additional details and outcomes by specific population group.)

For our 18-month horizon, taking no action and avoiding any economic or behavioral restrictions results in $20 trillion of damages, primarily due to the loss of 2 million lives. Isolating vulnerable persons without other behavioral change (VI) reduces deaths by 42%, and requiring non-vulnerable persons to adopt social distancing (VD) means avoiding 65% of the deaths under NP, but the loss of life is still considerable. Although vulnerable people take strong protective measures, they still interact on occasion with the rest of society, which adopts less effective measures. Keeping teleworkers and high school students at home (SD) saves an additional half a

[26] See also Pindyck (2020).

[27] Indeed, readers are encouraged to apply their own judgements about valuation parameters.

million lives, the value of which is 20 times those of the indicative school closing costs.[28] Keeping all children home saves an additional 300,000 lives and also protects essential workers, whose sick time falls by 70%. However, the benefits in additional lives saved by locking down all but essential workers (LD) are outweighed by the substantial wage loss of the nonessential outside workers.[29]

Table 2. Outcomes and Social Costs under Different Policies (Benchmark Calibration)

	NP	VI	VD	SD	WD	LD
Never infected (%)	2%	17%	42%	67%	92%	97%
Lost lives (millions)	2.05	1.19	0.73	0.43	0.12	0.05
Adults in isolation (millions)	-	-	88.0	149.1	209.7	262.2
Children in isolation (millions)	-	-	-	13.0	73.6	73.6
Cost of school shutdown (billion $)	-	-	-	253	1,436	1,436
Lost wages from isolation (billion $)	-	-	-	-	-	4,094
Lost wages from illness (billion $)	18	17	12	6	2	1
Value of illness burden (billion $)	262	219	146	87	21	7
Value of lost lives (billion $)	20,547	11,896	7,250	4,306	1,179	456
Total social cost (trillion $)	**20.1**	**12.1**	**7.4**	**4.7**	**2.6**	**6.0**

In the benchmark case, WD is the least-cost policy, at $2.6 trillion. This ranking can change, however, depending on the effectiveness of social distancing measures in reducing the CI rate. Table 3 reports the results for total social costs for a variety of sensitivity analyses. If social distancing practices outside the home can be improved (to a 60% rather than a 50% reduction from normal practice), lives are saved across all policies, enough so that the benefits of opening primary schools outweigh the costs. SD becomes the least-cost policy, and the $1.5 trillion in cost savings relative to the benchmark case indicate the social value of improving social distancing. On the other hand, if social distancing only reduces the CI rate by one third, the policy ranking is unchanged from the benchmark, but the least cost is nearly doubled to $4.9 trillion. If, added to this less effective social distancing, vulnerable persons can be kept no better isolated than average

[28] We are not distinguishing between the cost of schooling a teen versus a primary school student at home; the former is likely more independent and able to engage in distance learning, but the material also becomes more complex and difficult to home school.

[29] Using h = 37% (the Dingel and Nieman (2020) share of teleworkers) instead lowers costs by 17% in LD, due to smaller wage losses, and by 13% and 16% in WD and SD, respectively, due to lives saved.

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stay-at-home people (90% less than normal practice, rather than 95%), lockdown becomes the least-cost policy, with an even higher price tag of $6.5 trillion.

The last four rows concern uncertainties about the disease itself. If children turn out to be less likely to transmit the disease than adults, their interaction burden on the rest of the population is lowered; at a 50% lower rate, the benefits of keeping primary schools open just about outweigh the costs, making SD and WD roughly equal. If the rate of asymptomatic cases is instead at the lower end of the range of estimates, 50%, 3 million more people would die under no intervention, and 170,000 more even with WD, explaining the increase in costs. Finally, the possibility of reinfection would make the unchecked virus extremely deadly. If 50% of the recovered population became susceptible again within 6 months, the costs are much higher with few restrictions, but more similar to the benchmark with stringent policies. Finally, if no immunity is conferred, every person could expect to have a symptomatic case over the time horizon in NP, and the costs increase by an order of magnitude. The value of strong restrictions then becomes much higher; WD saves over 99% of the costs of NP, and is sufficiently effective that a full lockdown is not necessary.

Table 3. Sensitivity of Total Social Cost (Trillion $) to Parameter Assumptions

	NP	VI	VD	SD	WD	LD
Benchmark case	20.8	12.1	7.4	4.7	**2.6**	6.0
Social distancing more effective	20.8	12.1	2.5	**1.1**	1.9	5.9
Social distancing less effective	20.8	12.1	9.8	7.4	**4.9**	6.2
"" and isolating vulnerable persons less effective	20.8	14.6	12.2	9.6	6.6	**6.5**
Children less infectious	20.7	11.2	5.5	2.4	2.4	6.0
Asymptomatic rate lower	52.0	30.3	18.4	11.1	**4.4**	6.7
Less immunity	45.3	23.4	11.1	6.6	**2.8**	6.0
No immunity	453.7	256.1	120.5	54.7	**3.4**	6.0

In no case is vulnerable distancing the least cost policy. Although it saves many more lives than with no policy, there is added value to keeping more of the population at home, particularly those who can do so without losing their earnings. Of course, the assumption that those who can telework suffer no costs from isolation strains belief, and we discuss such caveats in the final section. However, the substantial cost differences between the VD and SD scenarios are indicative

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of the magnitude of the benefits that would be required to justify allowing teleworkers and distance learners to return to the open, even with social distancing.

Overall, we get a sense that the least-cost amount of distancing or reopening, practiced over this extended period, is likely short of a full lockdown, and likely involves keeping at home those people who do not risk their livelihoods by doing so. How many of the non-essential outside workers should be allowed to return to circulation depends strongly on the effectiveness of social distancing measures.

A way to think about the tradeoff of returning to work is by comparing the private benefits to the external costs for an *individual* that chooses to emerge from stay-at-home restrictions. For an individual that can only earn a living working outside the home, the main private benefits are the wages, which over 18 months amount to $78,000 dollars for the average worker of this type. An individual may weigh those against expected private costs from leaving home, which occur due to the extra risk of infection (here assumed to include uninsured medical costs and unpaid sick leave) and of death. However, that worker also increases the risks for others, imposing external costs on society. To estimate these costs, the population in the model is deviated so that the equivalent of one worker leaves home and returns to circulation, allowing the marginal change in the total social costs to be calculated.

Table 4 presents the results for the benchmark case and for several cases of sensitivity analysis. The risks for an individual worker depend both on the effectiveness of social distancing and the behavior of others, as determined by the policy scenario, as well as the underlying epidemiology. Starting from the most restrictive, near lockdown policy, the first non-essential outside worker to emerge from home and start working has an expected personal cost from added risk of just about $350 in the benchmark, and imposes an additional expected $4,500 on others. Both costs increase by an order of magnitude for an individual entering an environment with more people in circulation. For the last person to join simple distancing, the external costs are over $50,000, although this figure is still outweighed by the average wages gained by someone who cannot work at home. More effective social distancing—reducing those CI rates by 20% from the benchmark—reduces these external costs by 70% or more.

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Table 4. Private and External Social Costs (Change in Expected Cost of Illness and Mortality) for an Individual Emerging from Stay-at-Home Restrictions ($)

	Last to join SD / First to join VD	Last to join WD / First to join SD	Last to join LD/ First to join WD
Benchmark case			
Private cost	4,180	1,230	350
External cost	**53,390**	**32,080**	**4,510**
Social distancing more effective			
Private cost	610	260	160
External cost	11,960	3,250	1,440
Social distancing less effective			
Private cost	6,500	4,260	730
External cost	46,710	75,360	14,420
Asymptomatic rate lower			
Private cost	10,360	2,980	860
External cost	133,550	77,480	11,000
No immunity			
Private cost	58,190	2,270	370
External cost	1,145,290	116,730	5,110

When social distancing is *less* effective, it both raises own and external costs, but disproportionately for the early "emergers" than the later ones. Hence, the costs to bring an additional person into circulation from WD are higher than for SD, which leaves fewer susceptible people available to infect. (However, recall from Table 3 that total social costs are still increasing, just at a slower rate). Finally, if the disease turns out to be more burdensome—or particularly if little or no immunity is conferred from infection—the marginal costs of an individual re-entering the outside world can become quite large and increase steeply with the number of people in circulation. In these cases, some workers who cannot work at home should still stay there, since the total social costs of the last worker to join working-while-distancing exceed the average wages. However, in no case do the external costs of the first worker to leave lockdown exceed the average wages.

The external costs can also be viewed as the external benefits of going into isolation. Without immunity, the value of someone leaving vulnerable distancing and isolating themselves has a magnitude of over $1 million, or more than 20 times the cost in the benchmark parameterization. Even the private benefits should make teleworkers want to stay home. Therefore, understanding immunity—or developing a vaccine—would be invaluable for sound decisionmaking.

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6. Conclusion and Caveats

In this paper, a classic SIRD model is extended to reflect different categories of people in society and the economy, including those who are more vulnerable to COVID-19, essential workers, children, and those for whom following guidelines to stay at home does not jeopardize their livelihoods. Calibrated to the available evidence of the epidemiology of the novel coronavirus and the US population, the model estimates the cost-effectiveness of different degrees of stay-at-home restrictions and effectiveness of social distancing measures, as well as the value of better understanding underlying disease parameters.

The results confirm that despite the cost of disruptions from restrictions, business-as-usual would by far be the costliest option because of the staggering loss of life. Considering both wages losses and the value of lost lives, a lockdown of all nonessential workers, as imposed temporarily in Wuhan and Italy, is not likely to be cost-effective for an extended period. For the most part, if all those who can stay home do, the social costs of allowing those who cannot work from home to rejoin the economy are balanced by the benefits in terms of earnings. This situation may characterize the Dutch experience, where some nonessential businesses have always been allowed to operate, with moderate social distancing measures outside the home. The next question is whether the benefits of keeping schools open exceed the external costs; doing so may be seen in a trade-off with how many nonessential outside workers return to circulation; knowing whether children are less infectious than adults would help inform such a social choice.

The more effective the social distancing measures, the more people can be safely allowed to circulate. Thus, the success of the Swedish model of simple distancing relies critically on the effectiveness of the social distancing measures taken by people outside the home. However, a point of caution is found for jurisdictions considering further opening: all cases indicate that those people who do not risk their livelihoods by staying at home should still do so, since by circulating they would impose substantial external costs on society—on the order of tens of thousands of dollars each—without earning additional wages to offset those costs. Vulnerable populations in particular benefit greatly not only from being isolated but also from stay-at-home workers' isolating themselves as well. These actions also help protect essential workers.

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Of course, this exercise cannot calculate all of the costs of the disease and restrictive measures. Beyond wages and VSL, macroeconomic multipliers, interconnected supply chains, and other equilibrium economic feedback effects may be important.[30] Such effects would lend support to keeping more people engaged in the economy. Nor does our limited time horizon include all the benefits of restrictive measures, such as the value of being better positioned for the time afterward, if widespread vaccination or reliable treatment does not arrive.[31] This exercise concentrated on policies that are uniform over time; future research could consider short-duration, phased, or sequenced measures—are waves of strict interventions more cost-effective than continuous intermediate interventions?

Finally, personal utility is more than the value of things one can consume with income. People very much value the interactions they have with others, such as seeing friends and coworkers in person, gathering for concerts and events, and traveling. Socially minded people can consider weighing these additional benefits against the external costs they would impose. People may also have a disutility of being sick, not to mention the stress of worrying about health risks to themselves and their loved ones. Isolation itself brings risk of elevated mental and physical health issues.[32] Such nonmarket values would be an interesting area for further research by economists.

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[30] See, for example, Bodenstein et al. (2020) and Caballero and Simseck (2020).
[31] Acemoglu et al. (2020) consider uncertainty about vaccine arrival.
[32] Reger et al. (2020).

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9. Appendix

Table A-1. Contact and Infection Rate Assumptions, by Policy

	β_v	β_w	β_h	β_e	β_k	β_c
NP	β_0	β_0	β_0	β_0	β_{c0}	β_{c0}
VI	β_m	β_0	β_0	β_0	β_{c0}	β_{c0}
VD	β_m	β_d	β_d	β_d	$(\beta_{c0}/\beta_0)\beta_d$	$(\beta_{c0}/\beta_0)\beta_d$
SP	β_m	β_d	β_l	β_d	$(\beta_{c0}/\beta_0)\beta_l$	$(\beta_{c0}/\beta_0)\beta_d$
WD	β_m	β_d	β_l	β_d	$(\beta_{c0}/\beta_0)\beta_l$	$(\beta_{c0}/\beta_0)\beta_l$
LD	β_m	β_l	β_l	β_d	$(\beta_{c0}/\beta_0)\beta_l$	$(\beta_{c0}/\beta_0)\beta_l$

Table A-2. Contact and Infection Rate Assumptions, by Sensitivity Scenario

	β_0	β_{c0}	β_d	β_l	β_m
Benchmark	0.3	0.3	0.15	0.03	0.015
Social distancing more effective	0.3	0.3	0.12	0.03	0.015
Social distancing less effective	0.3	0.3	0.2	0.03	0.015
Social distancing and isolation less effective	0.3	0.3	0.2	0.03	0.03
Children less infectious	0.3	0.15	0.15	0.03	0.015

Table A-3. Detailed Outcomes by Population Group in the Benchmark Calibration

	NP	VI	VD	SD	WD	LD
Overall death rate from infection	0.6%	0.4%	0.4%	0.4%	0.5%	0.5%
Case fatality rate	3.0%	2.1%	1.9%	1.9%	2.2%	2.5%
Time infected (million weeks)						
Vulnerable	169.6	85.8	50.0	30.0	8.2	3.5
Essential workers	122.1	118.2	81.1	54.8	15.3	5.2
Outside workers	103.0	99.8	68.5	46.2	12.9	2.5
Home workers	94.5	91.5	62.8	22.4	6.0	2.3
Adolescents	25.5	24.7	17.0	6.1	1.6	0.6
Children	119.3	115.6	79.3	53.5	7.6	2.9
Deaths (thousands)						
Vulnerable	466.3	215.2	100.5	40.6	17.8	8.8
Essential workers	16.6	15.8	8.8	3.9	1.6	0.4

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Outside workers	14.0	13.3	7.4	1.6	0.7	0.3
Home workers	23.3	22.1	12.3	5.4	2.2	0.9
Adolescents	0.10	0.09	0.04	0.01	0.00	0.00
Children	0.21	0.19	0.09	0.04	0.01	0.00

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The Covid-19 shock and equity shortfall: Firm-level evidence from Italy

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This paper estimates the drop in profits and the equity shortfall triggered by the Covid-19 shock and the subsequent lockdown, using a representative sample of 80,972 Italian firms. We find that a 3-month lockdown entails an aggregate yearly drop in profits of €170 billion, with an implied equity erosion of €117 billion for the whole sample, and €31 billion for firms that became distressed, i.e., ended up with negative book value after the shock. As a consequence of these losses, about 17% of the sample firms, whose employees account for 8.8% of total employment in the sample (about 800,000 employees), become distressed. Small and mediumsized enterprises (SMEs) are affected disproportionately, with 18.1% of small firms, and 14.3% of medium-sized ones becoming distressed, against 6.4% of large firms. The equity shortfall and the extent of distress are concentrated in the Manufacturing and Wholesale Trading sectors and in the North of Italy. Since many firms predicted to become distressed due to the shock had fragile balance sheets even prior to the Covid-19 shock, restoring their equity to their pre-crisis levels may not suffice to ensure their long-term solvency.

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> "Is giving the already overleveraged corporate sector loans to infinity a good idea? [...] Might we all then be better off if these loans were fast converted into equity — strengthening corporate balance sheets and leaving the government with a portfolio of equity stakes along the way?" (Merryn Somerset Webb, *Financial Times*, 1 May 2020)

> "We have a huge opportunity now to replace government lending to companies in the Covid-19 crisis with equity purchases. Indeed, at current ultra-low interest rates, governments could create instantaneous sovereign wealth funds very cheaply." (Martin Wolf, *Financial Times*, 5 May 2020)

1 Introduction

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All great economic crises pose two equally important challenges: they drain the liquidity necessary for the functioning of firms, and burn equity capital, or part of it. Of these two, the first poses the most immediate challenge today: due to the COVID-19 shock, and the resulting lockdown, many companies have seen their revenues vanish even while their costs continue to mount and, therefore, find themselves in a liquidity crisis. To limit the recessionary effect of the shock, governments and central banks around the world have enacted policies aimed at providing liquidity to companies, either directly, or through the banking system. For instance, in March 2020, the European Central Bank (ECB) eased the conditions of its Targeted Longer-Term Refinancing Operations (TLTRO III) to support firms' access to bank credit, enlarged the list of corporate collateral eligible assets, and expanded the range of assets eligible for its purchases under the Corporate Sector Purchase Program (CSPP) to include non-financial commercial paper. At the same time, several Eurozone governments offered export guarantees, liquidity assistance, and credit lines to firms, through their respective national development banks, ranging from 38.6% of GDP in Germany and 29.8% of GDP in Italy, to 14% in France and 9.1% in Spain (Anderson et al., 2020).

Such generous liquidity support, however valuable to enable firms to survive in the short term, is far from sufficient in the medium and long term. Indeed, as liquidity reaches companies through loans, it increases their leverage, hence raising their default risk and leaving them vulnerable, with little room to invest and grow. The debt overhang problem arising from excessive debt accumulation is known to deter firm investment (see Myers (1997) and Hennessy et al. (2007)), and to slow down the pace at which corporate investment and growth recover from crises (Kalemli-Ozcan et al., 2019). Hence, if firms emerge from the COVID-19 crisis overloaded with debt, then investment and growth, which have already been sluggish in most of the Eurozone, will likely slow even further to a snail's pace. In other words, barring an adequate capital injection in its firms, the Eurozone could experience an "L-shaped" recession, with persistently depressed economic activity, rather than a "V-shaped" one, featuring a rapid recovery.

This highlights the urgent need to think about solvency, not just liquidity, and to inject new *equity*, not just liquidity, into viable firms. Some governments are already moving in that direction. The German federal government has already allocated €100 billion to inject equity and buy stakes in (large) companies affected by the COVID-19 shock via the Economic Stabilisation Funds (i.e., Wirtschaftsstabilisierungsfonds - "WSF"), €50 billion in direct grants to distressed one-person businesses and micro-enterprises, and €2 billion to expand venture capital financing to start-ups, new technology companies and small businesses. This federal funding is complemented by €33.5 billion funded by the States of Bavaria, Hesse and Baden-Wuerttemberg. But these seemingly large equity injections, which amount to 5.4% of GDP, are less than 1/7 of the liquidity being provided by the German government in the form of debt (38.6% of GDP). Meanwhile, the equity injections provided to firms by other Eurozone governments pale in comparison to the German figures, in particular due to the existing significant sovereign debt obligations in some of these countries.

Clearly, assessing how much equity capital will eventually be "burnt" in the ongoing crisis is a key pre-requisite to understanding the size of the equity injection that would be required to rebalance the capital structure of Eurozone firms, and get them on their feet again, as the crisis abates. In this paper, we attempt such a detailed exercise for Italy, the first economy in Europe to be seriously affected by the COVID-19 outbreak, and one of the most stressed since then. Our analysis consists of estimating the net income losses due to the lockdown for a large, representative sample of 80,972 Italian firms, which accounts for the substantial proportion of the Italian economy. Our analysis, which is based on 2018 data (the latest available), aims at quantifying the changes in firm leverage and consequent distress due to the lockdown resulting from the COVID-19 outbreak.

We hasten to emphasize from the onset that this is an exercise fraught with difficulties, since the crisis may unfold in a manifold of ways. The main unknown in our analysis is whether the Italian economy will experience a sharp but short recession, with a fast rebound in 2021, or rather one leading to a depressed economy for years to come, or some intermediate variant. To some extent, this depends on how the pandemic itself develops: while the initial lockdown has already lasted for almost three months, possible subsequent waves of the epidemic may require further lockdown periods in the future, possibly restricted only to some regions. Therefore, we consider a range of possible scenarios, which differ in the duration of the lockdown, so as to allow for a possible resurgence of the disease.

To identify the effects of the COVID-19 shock, we assume that it will induce a drop in firm revenues in each sector that is proportional to the fraction of value added forgone in the corresponding industrial sector as a result of the lockdown, while taking into account wage subsidies paid to inactive workers and reduced tax payments. This fraction is based on information regarding how essential each sector is to the population as deemed by the government, and how much it depends on close physical contact between workers and with customers. Based on the firms' estimated profit reduction, we can calculate the aggregate profit reduction for the whole sample, and the equity shortfall for all firms, as well as for the subsample of distressed firms, i.e., those ending up with negative book value of equity (net worth), as well as their distribution by firm size, sector, and geographical area.

We find that after a three-month lockdown, the firms in our sample are estimated to face an aggregate annual profit drop of €170 billion (roughly 10% of GDP in 2018). For the subsample of firms predicted to have losses, the aggregate equity erosion is estimated to amount to €117 billion (roughly 7% of Italian GDP in 2018). The shock is estimated to force about 13,500 firms (i.e., 17% of the total) into negative net worth territory; overcoming the equity shortfall of these distressed firms would require an equity injection of €31 billion. The companies predicted to have negative net worth by the end of the year employ slightly over 800,000 workers, that is, 8.8% of the employees of our sample firms.

Of course, if all of these distressed firms were to go bankrupt and be liquidated, the resulting increase in unemployment would be very large. This raises the question of whether our prediction is too pessimistic. On the one hand, our estimates might indeed be regarded as an upper bound, since the liquidity injections and guarantee programs enacted by the Italian government – currently amounting to €530 billion – may enable

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many of these firms to avoid bankruptcy and survive at least for some time, even though they may have negative net worth, in book terms. Other firms may be able to raise fresh equity capital, or to restructure their debt so as to return to solvency.

On the other hand, however, our methodology could be questioned for resting on premises that are too optimistic as we do not consider the spillover effects between sectors due to the lockdown, the drop in demand likely to materialize once the lockdown is lifted, nor the increase in firms' costs due to social distancing requirements. In fact, our present calculations assume firms revert to their normal pre-COVID-19 revenue and cost structure *immediately* after the lifting of the lockdown while, in practice, they are most likely to do so only gradually, especially in sectors where social distancing rules are more problematic, such as Retail Trade and Tourism.

Insofar as the sectors most affected by the lockdown were to revert only slowly to their pre-COVID-19 levels after the lockdown is lifted, the estimated equity funding needed to recapitalize Italian firms would rapidly escalate beyond the above-reported figures. This is because the shortfall grows non-linearly due to the convex characteristics of equity, especially for near-distressed companies with thin equity cushions, since equity enjoys limited liability, even if the drop in profits (relative to a no-COVID-19 scenario) is assumed to grow linearly in the duration of the lockdown. Indeed, if the reversion to near-normalcy is not so immediate, then our estimates for the six-months lockdown scenario would be the most appropriate, implying a profit reduction of €321 billions (18% of the GDP in 2018) and a total equity shortfall of €259 billions. This would push more than 30% of firms into distress with a total negative equity equal to €126 billion.

We also find that the COVID-19 shock would affect different firms with greatly disparate severity. Large companies are predicted to fare better than small and medium-sized enterprises (SMEs) for any assumed duration of the lockdown as they are generally better capitalized to start with: a three-month lockdown is predicted to lead to a 18.1% default rate for small firms, and a 14.4% default rate for medium-size ones, against only 6.4% for large firms. As small firms are under-represented in our sample, this provides an additional reason to suspect that our predictions may well under-estimate the impact of the COVID-19 shock on the frequency of distress and its consequences for employment.

Our results show that the firms that are projected to enter distress are typically not only smaller, but are also characterized by lower profitability and available cash, and to

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be far less capitalized than the entire sample. Moreover, such firms are generally much more labor intensive than other firms, as they have far more employees relative to total assets, and a cost structure where labor costs weigh relatively more in total costs. These characteristics of the sample have two important implications. First, an equity injection that would bring these firms back to their pre-COVID-19 level would still not address their inherent financial fragility, and potentially expose them to a second round of external shocks. Second, as these firms are so labor intensive, their demise would imply many redundancies, with severe knock-on effects on demand, and indeed, the whole economy.

Our analysis also highlights that the effects of the lockdown on firms' profits differ vastly across industries. The profit drop is concentrated in Manufacturing and Wholesale Trading, which are respectively the first and third sectors by total assets and number of employees in Italy. Within Manufacturing, the most severely hurt sub-sectors are Fabricated Metal Products, Industrial and Commercial Machinery, Computer Equipment, and Transportation Equipment. Perhaps surprisingly, the profits and equity levels of firms in the Recreation Services and Tourism sectors are relatively lightly affected by the lockdown in our analysis. This may be the case because these sectors are highly labor intensive, so that most of their labor cost, i.e. their wage bill, is currently covered by public wage subsidies, insofar as they are inactive. However, the profitability of these sectors may also be affected by social distancing policies for a longer time than other sectors, due to the lower physical distance between employees and customers in these sectors, and in general, by sluggish consumer demand.

At the geographical level, the losses from the lockdown are more concentrated in the Northern regions, where most of Italian manufacturing firms, especially the largest ones, are headquartered. However, it should be emphasized that our results may underestimate the extent to which profits and equity levels will drop for firms located in Central and Southern Italy. The reason is that in the industrial structure of these regions, the Recreation and Tourism sectors loom larger than in Northern Italy, which, as just explained, may take much longer to recover than the Manufacturing sector, which effect is not accounted for by our estimates.

The paper proceeds as follows. Section 2 describes our dataset. Section 3 describes our methodology, while Section 4 presents our results. Our tentative conclusions are presented in Section 5.

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2 Data

We select all the non-financial Italian companies present in the ORBIS database of Bureau van Dijk that were active, employed more than 10 workers, and had at least €2 million of total assets in 2018. Hence, we exclude firms classified as micro-enterprises by the EU, mainly for consistency with the standard international definitions of small, medium and large companies, but also because data quality is typically worse for micro-enterprises.[1] Moreover, we retain in our sample only companies for which accounting data are available for 2017 and 2018. These screens in the construction of our dataset leads to a sample of 83,621 companies, for each of which we have balance sheet data for the period 2017-2018.[2] We focus on accounting data for 2018 because, at the time of writing, 2019 data are available only for a few companies.

We eliminate from our sample all firms with negative equity both in 2017 and 2018, as well as those for which the sum of Net Income in 2018 and Equity at the end of 2017 is negative: the rationale is that we aim to investigate the impact of the COVID-19 shock on solvent firms and, therefore, we exclude from our sample firms that would have been in distress in any case, even absent the COVID-19 shock. Thus, our evaluation provides an assessment of the *incremental* effect of the COVID-19 shock on the financial performance and distress of Italian firms, and *not* its total effect, which would include the normal vicissitudes of firm performance.

In addition to the overall sample, we analyze sub-samples stratified by firm size, by sector, and by geographical area of firm headquarters. Firms are classified by size, based on the EU definitions, into three sub-samples of small, medium-sized and large. Sectors and geographical areas are defined in line with the Italian National Institute of Statistics (ISTAT). Sectors are defined at the first SIC digit level but, for the manufacturing sector, they are further broken down at the two-digit level.

We merge the balance sheet data for our sample firms with data on the forgone fraction of value added in each sector j due the lockdown. This variable, which we denote by

[1]Small firms are defined as those with less than 50 employees. Medium-sized firms are defined as those with between 50 and 250 employees. Large firms are defined as those with more than 250 employees and balance sheet totals of more than €43 million. See the classification by the EU Commission at https://ec.europa.eu/growth/smes/business-friendly-environment/sme-definition_en.

[2]Specifically, we downloaded the following items: Total Assets, Shareholders' Funds, Operating Revenue, Number of Employees, Net Income, Return on Equity (ROE), Financing Expenses, Employee Costs, Cash and Cash Equivalents, Debt, and Equity (Net Worth).

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λ_j for sector j, is computed from national accounting data, firm sectoral data and Labor Force Survey data (ISTAT), as well as the Profession Sample Survey (INAPP), to take into account the fraction of employees in "teleworking" mode in each sector. The fraction of forgone value added in each sector reflects the fraction of non-essential industries in that sector, based on the lists contained in governmental decrees (DPCM of 9, 11 and 22 March, and MISE decree of 25 March 2020).

The values of λ_j for each sector are reported in Table 1. The table shows that the sectors most severely affected by the lockdown are Other Services (80.6%), Recreation Services (74.2%), Restaurants and Tourism (62.1%), Manufacturing (48.7%) and Construction (48.2%). We note the large variance within the Manufacturing and Construction sectors, as reported in the second and third panel of Table 1. In particular, within the Construction sector, we estimate a λ_j of 87.6% for General Contractors and Operations, and 5.2% for Heavy Construction. For Manufacturing, we estimate 84.5% for Furniture and Fixtures, and 5.3% for Chemicals and Allied Products.

Moreover, the distribution of firms differs widely across sectors and sub-sectors, as shown by the second column of Table 1. This aspect has an important bearing on our analysis. For example, the Restaurants and Tourism sector is significantly affected by the lockdown, but only 3,086 firms are in that sector, accounting for less than 4% of our sample. Conversely, the Manufacturing sector, which is on average less affected by the lockdown than the Restaurants and Tourism sector, represents more than 37% of the firms in our sample. As we shall see, the severity of the equity shortfall that we estimate will reflect the combination of these two aspects, i.e., (i) the severity of the lockdown in each sector and (ii) the number and type of firms belonging to that sector.

After merging firm-level data with our measure of the lockdown's severity, and cleaning and filtering the resulting data, we are left with a final sample of 80,972 companies and 9.014 million of employees. The first column in Table 2 provides the summary statistics for the whole sample as of 2018: all data are in millions of euros, except for the number of employees that is stated in units. For completeness, we also provide summary statistics on Total Equity at the end of 2017, because, as we mentioned above, we consider only firms that have a positive book value of equity, at the end of both 2017 and 2018.

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Table 1: Fraction of Value Added and Number of Firms Affected by the Lockdown

This table provides data on the fraction of value added lost, λ_J, for sector j, and the number of firms in sector j, computed from national accounting data, firm sectoral data and Labor Force Survey data (ISTAT), as well as data from the Profession Sample Survey (INAPP). These estimates take into account the fraction of employees in "smart-working" mode in each sector. The fraction of forgone value added in each sector reflects the fraction of non-essential industries in that sector, based on the lists contained in governmental decrees (DPCM of 9, 11 and 22 March, and MISE decree of 25 March 2020).

Sector j	Fraction of Sector's Value Added Affected by Lockdown (λ_j)	No. of Firms in Sector j
Sectors		
Agriculture and Food	5.3	4,829
Business services	2	7,972
Communications	.3	239
Construction*	48.2	6,545
Education	2.2	295
Energy and Gas	0	1,796
Extraction	29.4	342
Health	0	1,158
Manufacturing**	48.7	30,457
Other services	80.6	1,758
Real Estate	5.2	811
Recreation Services	74.2	780
Restaurants and Tourism	62.1	3,086
Transportation	0	4,566
Wholesale Trade	42.1	16,338
***Construction**		
General Contractors and Operations	87.6	2,566
Special Trade Contractors	44.5	3,072
Heamy Construction, Except Building Construction	5.2	907
****Manufacturing**		
Apparel, Finished Products from Fabrics	69.9	1,070
Chemicals and Allied Products	5.3	1,634
Electronic and Other Electrical Equipment	38.7	1,870
Fabricated Metal Products	78.7	6,640
Furniture and Fixtures	84.5	1,070
Industrial and Commercial Machinery	64.2	5,509
Leather and Leather Products	89.4	546
Lumber and Wood Products, Except Furniture	79.6	896
Measuring, Photographic, Medical and Optical	40.4	699
Miscellaneous Manufacturing Industries	27.5	557
Paper and Allied Products	19.2	1,171
Petroleum Refining and Related Industries	29.4	103
Primary Metal Industries	78.7	1,463
Printing, Publishing and Allied Industries	48.7	979
Rubber and Miscellaneous Plastic Products	45.4	2,571
Stone, Clay, Glass, and Concrete Products	70.1	1,461
Textile Mill Products	68.1	1,291
Transportation Equipment	76.7	927

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Table 2: Characteristics of All Firms in 2018

This table provides summary financial information for our sample of 80,972 companies. All average values refer to 2018 balance sheet figures. Total Equity is reported both in 2018 and 2017. Column (1) provides summary statistics for the entire sample of firms. Column (2) provides summary statistics for firms that register equity shortfalls after a 3-month lockdown. Column (3) provides summary statistics for firms in distress (defined as negative book equity) after a 3-month lockdown. The source of our data is Orbis (Bureau Van Dijk) and the equity shortfall estimates are based on our computations. All figures in the table are in millions of euros. Number of employees are in units.

	Firms in 2018 (1)	Firms with equity shortfalls after a 3-month lockdown (2)	Firms in distress after a 3-month lockdown (3)
Total Assets	44.31	29.07	13.75
Total Equity	16.61	9.83	1.44
Total Equity (2017)	15.35	9.44	1.29
Operating revenues	36.52	29.98	25.16
Net Income	1.29	0.36	0.11
Total cost net of employees' costs and tax	29.41	25.60	22.69
Cost of employees	4.97	3.67	2.25
Taxation	0.60	0.35	0.11
Number of Employees	111.32	84.26	58.46
ROE	10.66	6.46	9.11
ROA - EBIT over Total assets (%)	6.25	4.34	3.57
Z-score	6.80	6.30	4.43
Total Equity over TA (%)	32.81	29.68	10.46
Net working capital over Total assets (%)	21.24	19.23	8.31
Cash over TA (%)	10.70	9.03	7.18
Observations	80,972	57,248	13,529

Tables 3, 4 and 5 provide the same summary statistics for the three sub-samples of large, medium-sized and small firms. The tables show that, on average, large, medium and small firms employ 1,544, 128 and 23 employees, respectively. Firms differ also in terms of their accounting ratios. In particular, equity capitalization (defined as Equity over Total Assets) is higher for large firms (38.12%) than for medium-sized and small ones (32.51% and 32.6%, respectively). Their lower capitalization makes small and medium firms potentially more fragile than large ones in the face of adverse shocks to their profitability. The Return on Equity (ROE) is higher in small firms (10.94%) and medium ones (10.22%) than in large firms (8.17%), but the difference narrows considering the Return on Assets (ROA, i.e., Earnings Before Interest and Taxes over Total Assets), which is, on average, 6.27% for small firms and 6.19% for large ones. However, Cash over Total Assets ranges from 10.97% for small firms to 8.91% for large ones, so that the former have a larger liquidity buffer.

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Table 3: Characteristics of Large Firms in 2018

This table provides summary financial information for our sample of 3,461 large companies. All average values refer to 2018 balance sheet figures. Total Equity is reported both in 2018 and 2017. Column (1) provides summary statistics for the sample of large firms. Column (2) provides summary statistics for firms that register equity shortfalls after a 3-month lockdown. Column (3) provides summary statistics for firms in distress (defined as negative book equity) after a 3-month lockdown. Large firms are defined as those with more than 250 employees and balance sheet total assets of more than €43 million. The source of our data is Orbis (Bureau Van Dijk) and the equity shortfall estimates are based on our computations. All figures in the table are in millions of euros. Number of employees are in units.

	Firms in 2018 (1)	Firms with equity shortfalls after a 3-month lockdown (2)	Firms in distress after a 3-month lockdown (3)
Total Assets	703.64	496.51	279.18
Total Equity	257.16	172.18	30.41
Total Equity (2017)	244.43	168.16	29.98
Operating revenues	521.56	490.57	566.19
Net Income	19.58	5.30	0.08
Total cost net of employees' costs and tax	418.40	419.90	520.19
Cost of employees	72.08	58.77	44.15
Taxation	9.33	6.61	1.77
Number of Employees	1543.65	1287.72	1068.79
ROE	8.17	1.60	-4.41
ROA - EBIT over Total assets (%)	6.19	4.01	2.42
Z-score	6.75	6.20	4.20
Total Equity over TA (%)	38.12	35.13	14.40
Net working capital over Total assets (%)	17.24	15.03	4.06
Cash over TA (%)	8.91	7.42	5.62
Observations	3,416	1,860	219

Table 4: Characteristics of Medium Firms in 2018

This table provides summary financial information for our sample of 18,837 medium companies. All average values refer to 2018 balance sheet figures. Total Equity is reported both in 2018 and 2017. Column (1) provides summary statistics for the sample of medium firms. Column (2) provides summary statistics for firms that register equity shortfalls after a 3-month lockdown. Column (3) provides summary statistics for firms in distress (defined as negative book equity) after a 3-month lockdown. Medium-sized firms are defined as those with between 50 and 250 employees. The source of our data is Orbis (Bureau Van Dijk) and the equity shortfall estimates are based on our computations. All figures in the table are in millions of euros. Number of employees are in units.

	Firms in 2018 (1)	Firms with equity shortfalls after a 3-month lockdown (2)	Firms in distress after a 3-month lockdown (3)
Total Assets	33.80	31.87	22.60
Total Equity	12.91	10.68	2.40
Total Equity (2017)	11.88	9.88	2.08
Operating revenues	35.65	35.63	40.49
Net Income	1.09	0.45	0.21
Total cost net of employees' costs and tax	28.73	29.93	35.89
Cost of employees	5.34	4.92	4.21
Taxation	0.48	0.33	0.18
Number of Employees	128.30	118.93	117.69
ROE	10.22	5.09	6.74
ROA - EBIT over Total assets (%)	6.22	4.33	3.49
Z-score	6.63	6.17	4.25
Total Equity over TA (%)	32.51	30.12	11.31
Net working capital over Total assets (%)	20.14	17.95	5.39
Cash over TA (%)	10.19	9.00	8.27
Observations	18,837	12,287	2,699

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Table 5: Characteristics of Small Firms in 2018

This table provides summary financial information for our sample of 58,719 small companies. All average values refer to 2018 balance sheet figures. Total Equity is reported both in 2018 and 2017. Column (1) provides summary statistics for the sample of small firms. Column (2) provides summary statistics for firms that register equity shortfalls after a 3-month lockdown. Column (3) provides summary statistics for firms in distress (defined as negative book equity) after a 3-month lockdown. Medium-sized firms are defined as those with between 50 and 250 employees. The source of our data is Orbis (Bureau Van Dijk) and the equity shortfall estimates are based on our computations. All figures in the table are in millions of euros. Small firms are defined as those with less than 50 employees and balance sheet total assets of more than €2 million. The source of our data is Orbis (Bureau Van Dijk) and the equity shortfall estimates are based on our computations. All figures in the table are in millions of euros. Number of employees are in units.

	Firms in 2018 (1)	Firms with equity shortfalls after a 3-month lockdown (2)	Firms in distress after a 3-month lockdown (3)
Total Assets	9.33	8.10	6.02
Total Equity	3.80	2.57	0.61
Total Equity (2017)	3.14	2.47	0.50
Operating revenues	8.58	8.49	10.09
Net Income	0.28	0.12	0.08
Total cost net of employees' costs and tax	7.18	7.35	9.07
Cost of employees	0.98	0.93	0.89
Taxation	0.13	0.08	0.06
Number of Employees	22.55	22.44	22.54
ROE	10.94	7.06	10.00
ROA - EBIT over Total assets (%)	6.27	4.35	3.62
Z-score	6.86	6.34	4.48
Total Equity over TA (%)	32.60	29.33	10.16
Net working capital over Total assets (%)	21.82	19.78	9.14
Cash over TA (%)	10.97	9.10	6.93
Observations	58,719	43,101	10,611

Labor costs (Employee Cost) range from 0.98 to 72.08 million on average, and corresponds to an average cost per employee of €46,694 for large firms and €43,555 for small firms. Hence the cost per employee does not differ widely across firm sizes, implying that the public labor cost subsidy per employee during lockdown is quite balanced across firm size sub-samples. However, total costs net of employees' cost and tax, scaled by operating revenues are larger for small firms (about 83%) relative to medium-sized and large firms (slightly above 80%), indicating a higher operating leverage (fraction of fixed costs in total costs) for smaller firms in our sample.

To better assess the creditworthiness of these different firms, we employ the Altman Z-score based on the yearly values of four key financial ratios according to the formula proposed by Altman et al. (2014) for firms for which only the book value of equity (as opposed to the market value) is available. This calculation also allows us to assess to what extent firm solvency deteriorates as a result of the COVID-19 shock. For each firm

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i in the sample, we measure the Altman Z-score, according to

$$z_{it} = 3.25 + 6.56 \cdot x_{1it} + 3.26 \cdot x_{2it} + 6.72 \cdot x_{3it} + 1.05 \cdot x_{4it}, \tag{1}$$

where x_{1it} is the ratio of the Working Capital of firm i, at time t, to Total Assets, x_{2t} is the ratio of Capital Reserves to Total Assets, x_{3t} is Earnings Before Interest and Taxes scaled by Total Assets, and x_{4t} is the ratio of the Book Value of Equity to Total Liabilities, each measured in accounting year t. Tables 3, 4 and 5 show that the Z-score is very similar across firm size classes, as it ranges from 6.75 for large firms, to 6.63 for the medium, and 6.86 for the small firms. This indicates that, on average, there is no significant difference in terms of creditworthiness among the three types of firms that we investigate prior to the COVID-19 shock.

Comparing the number of firms and employees in our database with those reported by ISTAT for 2017 (the latest available data), it emerges that our sample under-represents small firms, as it does not include those with less that €2 million of Total Assets. ISTAT reports that firms with more than 9 employees (excluding Agriculture) have 7,808,000 employees, of which 40.5% are in small firms, 24.6% in medium firms, and 35% in large firms. In our sample, the share of employees working in small firms is only 15.3%, while the shares of employees in medium and large firms are 27.0% and 57.7% respectively, as illustrated by Figure 1. The figure also reports the allocation of Total Assets in our sample, which largely mirrors that of employees, i.e., 15.1%, 18.3% and 66.5% for small, medium and large firms respectively.

Figure 2 presents the distribution of Total Assets by sector: Manufacturing is the sector with the largest Total Assets (829 billion), followed by Business Services (618 billion), and both these sectors feature one or more large firms, as shown by Figure 3. A similar pattern emerges in Figures 4 and 5, which report the number of employees per sector and their distribution among small, medium and large firms.

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Figure 1: Shares of Total Assets and Employees in Large, Medium-Sized and Small Firms

The figure shows the proportions of large, medium-sized, and small firms in our sample, as defined by European Commission, in terms of total assets and employees. The source of our data is Orbis (Bureau Van Dijk) and the data are for 2018.

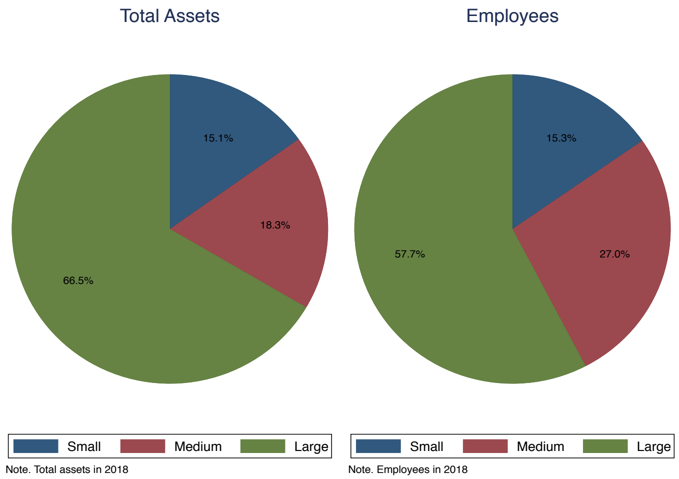

Figure 2: Total Assets by Sector

The figure shows the total assets by sector, in our sample, from national accounting and firm sectoral data as defined by ISTAT. The source of our data is Orbis (Bureau Van Dijk) and the data are for 2018.

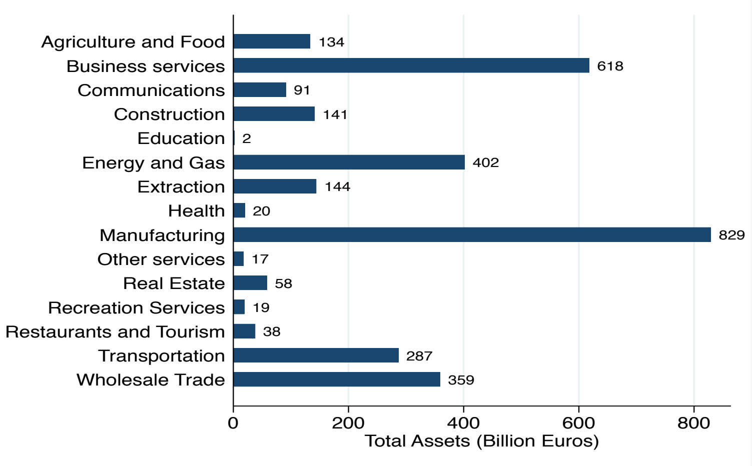

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Figure 3: Total Assets by Sector and Firm Size

The figure shows proportions of total assets of large, medium-sized, and small firms in our sample, as defined by European Commission, by sector, in our sample. The sector definitions are from national accounting and firm sectoral data as defined by ISTAT. The source of our data is Orbis (Bureau Van Dijk) and the data are for 2018.

Figure 4: Number of Employees by Sector

The figure shows the number of employees by sector, in our sample, from national accounting and firm sectoral data as defined by ISTAT. The source of our data is Orbis (Bureau Van Dijk) and the data are for 2018.

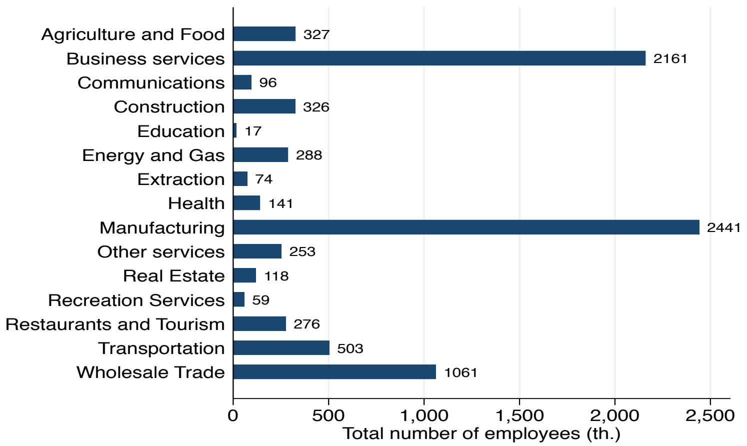
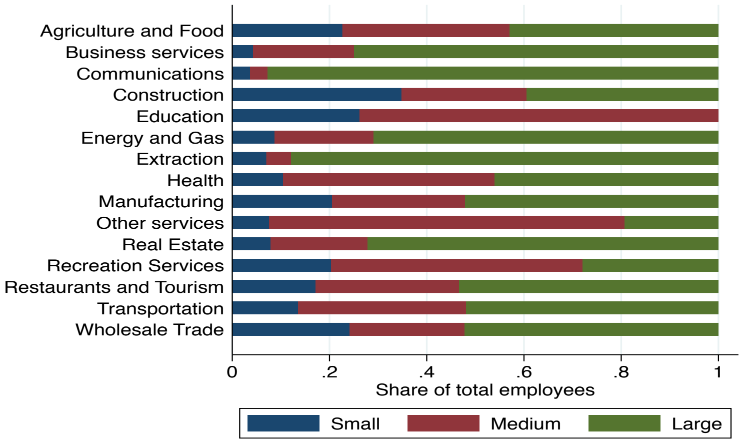


Figure 5: Share of Employees by Sector and Firm Size

The figure shows proportions of employees of large, medium-sized, and small firms in our sample, as defined by European Commission, by sector, in our sample. The sector definitions are from national accounting and firm sectoral data as defined by ISTAT. The source of our data is Orbis (Bureau Van Dijk) and the data are for 2018.



3 Methodology

Based on the above dataset, we estimate the net income losses due to the lockdown for each company in our sample. The key idea is to use 2018 balance sheet data for firms present in the ORBIS database at the end of 2017 and featuring a positive book value, and simulate the impact of the COVID-19 lockdown on their operating revenues, labor and non-labor costs, taxes and profits.[3] This approach has the disadvantage of basing our analysis on the Italian economic conditions in 2018, rather than in 2020, but has several advantages. First, the difference between the economic situation in Italy in 2018, and that at the beginning of 2020 before the COVID-19 shock was rather small due to anemic economic growth. GDP growth was 0.8% in 2018 and 0.3% in 2019, and its 2020 forecast by ISTAT was 0.6%. Therefore, the economic outlook and also the values we observe are roughly similar between 2018 and the projections for 2020. Second, simulating the COVID-19 shock based on actual historical data, rather than forecasts, provides an im-

[3]Orbis defines Operating Revenues as the sum of Revenues from Goods Sold, Production, Revenues from Sale or Fixed assets and Material Sold, Other Operating Revenues, and Transfer of Operating Revenues.

mediate counterfactual to evaluate the equity injections required to restore Italian firms' solvency following the COVID-19 shock. This rules out confounding factors due to potential estimation errors that may affect the forecast of balance-sheet variables of firms in 2020, absent the COVID-19 shock. Third, our approach is simple and intuitive: we effectively simulate what would have happened if the 2020 COVID-19 shock had occurred in an economic situation identical to that of 2018.

We proceed as follows. For firms in sectors unaffected by the lockdown, we consider the actual profits (or losses) realized in 2018, corresponding to operating revenues y_i minus labor costs w_i, non-labor costs z_i and taxes τ_i for 2018:

$$\pi_i = y_i - w_i - z_i - \tau_i, \tag{2}$$

In contrast, in sectors affected by the lockdown, both revenues and costs are assumed to be lower: on the one hand, the operating revenues of firm i in sector j are assumed to drop by the fraction of the sector j's value-added affected by the lock-down (i.e., the fraction λ_j shown in Table 1); on the other hand, the labor costs of firms operating in these sectors are correspondingly reduced, the wages of inactive employees being covered by the Italian government under its "Cassa Integrazione Guadagni"(CIG) scheme during the length of the lockdown. We capture this labor cost subsidy to affected companies by assuming that in sector j, firms save a fraction λ_j of their wage costs w_i. Non-labor costs, z_i, are considered fixed costs before taxes, which we assume to be independent of the COVID-19 shock. Taxes τ_i are instead assumed to drop by the same fraction as operating revenues for the duration of the lockdown. Hence, the yearly profit (or loss) for firm i in sector j, as a result of the shock, after X months of lockdown, is assumed to be:

$$\hat{\pi}_i(X) = (y_i - w_i - \tau_i)\left(1 - \frac{X}{12}\lambda_j\right) - z_i, \tag{3}$$

where the operating revenues y_i, the cost of employees w_i and taxes τ_i of firm i, are calculated by re-scaling each firm's revenues and variable costs in 2018 by the fraction of lockdown months $X/12$, multiplied by sector j's lockdown severity λ_j.

The annual profits of each company are simulated for six hypothetical scenarios featuring different lockdown durations – from 1 to 6 months. For each duration, the annual simulated profits of each firm are the sum of its profits during the lockdown period

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and those in the "normal" (i.e., non-lockdown) regime as defined by equation (2), each weighted by their respective fractional duration $X/12$ and $1 - X/12$.[4] Based on the simulated profits obtained as described above, we calculate the year-end equity shortfall for each company in the sample, defined as the difference between its equity at the end of 2017 and its profit shortfall associated with a hypothetical lock-down of X months in 2018. Hence, a firm is assumed to be distressed only if it is estimated to have negative net worth by the end of 2018, not by the end of the assumed lockdown period of X months. This implies that firms affected by the lockdown are assumed to go back to their normal level of revenues (and to lose eligibility for wage subsidies as well as tax reductions) as soon as the lockdown is lifted. Hence, assuming say a three-month lockdown, firms are predicted to have nine months of normal (i.e., no-COVID-19-affected) profits.

Reliance on end-of-2017 book values and on 2018 profit data may lead to overestimating the incidence of distress, as we neglect that profits in 2019 and 2020 may have allowed firms to achieve somewhat higher equity, if not distributed as dividends. Conversely, these assumptions may lead to an underestimate of the incidence of distress insofar as we ignore losses that firms may have experienced in 2019. Sticking to 2018 realized data enables us to avoid making assumptions (or producing predictions) about the dynamics of profit and losses of these firms in 2019 and 2020.

We also calculate the percentage of companies that are forced into distress by the lockdown, i.e. those whose year-end cumulative losses exceeds their entire initial equity, assuming a lockdown of X months. These are firms that, absent a re-capitalisation, are predicted to have year-end negative book value. Of course, these companies need not necessarily go bankrupt if they have access to liquidity in the form of bank loans or bond issuance, for instance as a result of government guarantees or if they can persuade their creditors to restructure their debt liabilities, or if they can raise fresh equity via new share issuance. It should also be noted that all our calculations are based on book values, and to the extent that market values deviate from the book values, it is possible that a firm may have a negative net worth on a book basis, and yet be viable in the eyes of the market (or the opposite).

[4]This assumes a uniform distribution of profits over the year and, therefore, neglects their seasonality, which may be important in some sectors such as Tourism. Of course, since the definition of the lockdown parameters themselves are estimates, this is not likely to be of any consequence for the first order calculations that we are attempting.

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Finally, it is worth highlighting two other possible limitations of our methodology. For simplicity, we assume (i) the lockdown to be lifted simultaneously in all sectors and (ii) the profits of each firm to go back to "normal" as soon as the lockdown is lifted. In practice, the lockdown period may differ somewhat across sectors, being shorter in productive sectors where social distancing is less problematic, such as Manufacturing, and longer in other sectors, such as Retail Trade, Entertainment and Tourism. Moreover, in most sectors, revenues and profits are likely to revert to the pre-lockdown level only gradually, and at different speeds: in sectors such as Tourism they are expected to take much longer to recover than in others, again because social distancing requirements pose greater challenges. On the whole, the fact that the post-lockdown recovery is going to be gradual in most sectors suggests that the 3-month lockdown scenario that we present as our baseline should really be considered as a lower bound: predicted losses, equity shortfall and defaults may well be more accurately approximated by those that we report for a longer lockdown period.

4 Results

The main objective of this paper is to assess the extent to which the lockdown due to the COVID-19 pandemic has eroded the equity of Italian firms by inflicting losses on them. As described above, data availability constraints force us to estimate the changes in firms' equity based on 2018 data, as if the lockdown had occurred in 2018. Figure 6 presents our estimates of the change in profits and the resulting equity shortfall for our entire sample of firms, for alternative scenarios regarding the duration of the lockdown. The green bars show the aggregate lockdown-induced change in profits for the whole sample relative to the no-lockdown case (which coincide with the actual profits and losses realized by these firms in 2018 – the counterfactual for our analysis). The red bars measure the aggregate equity shortfall, i.e., the total losses for the subsample of firms that, according to our simulation ,experience lockdown-induced losses and, thus, a reduction in the book value of equity relative to its initial level (as of the end of 2017). Finally, the blue bars measure the equity shortfall for the subsample of firms that due to the lockdown end up with negative year-end net worth, calculated as the sum of the initial equity (as of the end of 2017) and lockdown-induced negative profits (losses, simulated for 2018).

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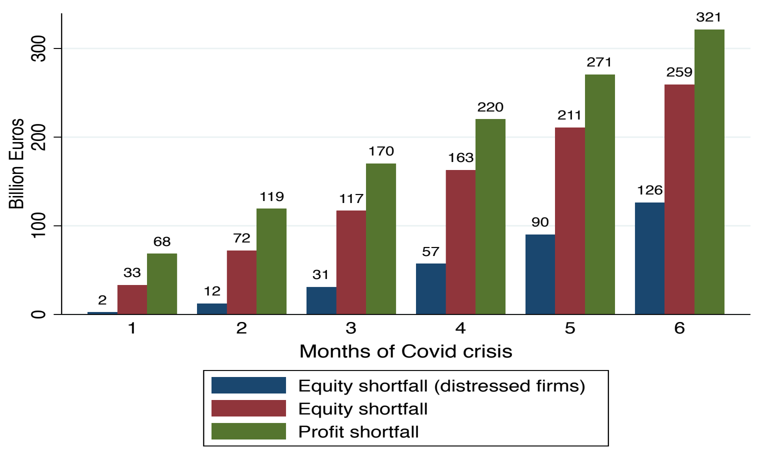
Figure 6: Equity and Profit Shortfall: All Firms

The figure shows the annual financial projections for all firms, based on data from Orbis (Bureau Van Dijk). Profit shortfall is defined as the difference between all firms' end-of-the-year profits after X months of lockdown and annual net income in 2018. Equity shortfalls is defined as the sum of all firms' end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined by the sum of all firms' end-of-the-year negative profits (losses) after X months of lockdown and the total equity at the end of 2017. Data source: Orbis (Bureau Van Dijk).



The figure shows that, after a three-month lockdown, the firms in our sample are projected to experience an annual drop in profits of €170 billion. Such a lockdown is sufficient to trigger aggregate losses (equity shortfall) of €117 billion, €86 billion of which arises in firms facing losses but retaining a positive year-end book value, and €31 billion in distressed firms. As shown in Table 2, a 3-month lockdown would erode the equity of 57,248 firms, i.e., 71% of firms in our sample. Moreover, it would force as many as 13,529 firms into distress out of 80,972 (see column 3), implying approximately a 17% default rate in the absence of any debt restructuring or equity injection, as shown also by the upper panel of Figure 7. Since these firms employ 790,905 employees, i.e. about 9% of the 9,013,803 employees in our sample, the employment drop resulting from their bankruptcy and liquidation would be of significant macroeconomic relevance.

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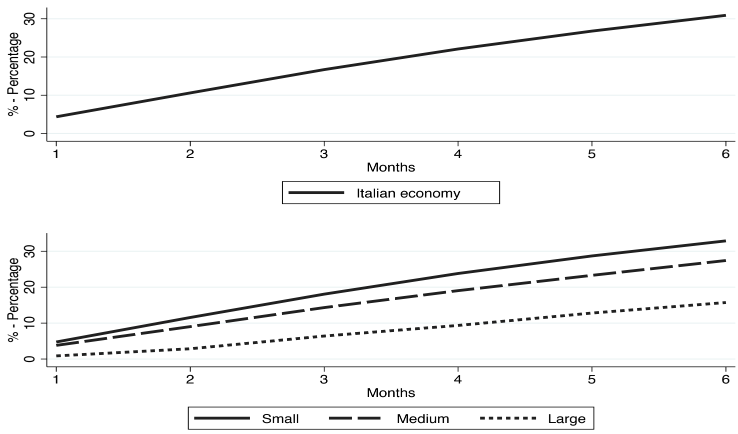
Figure 7: Distress Rate by Lockdown Duration

The figure shows the distress rates for all firms, based on data from Orbis (Bureau Van Dijk). Distress rate is defined for each firm in our sample when the annual losses after X months of lockdown exceed total year-end equity (taken to be equal to its book value at the end of 2017). The upper panel shows the number of firms predicted to be in distress divided by the total number of firms in the sample. The lower panel shows the same ratio for the sub-samples of large, medium-sized and small firms. Data source: Orbis (Bureau Van Dijk).



The firms facing an equity shortfall, and especially the subset of those that are also in distress, are mostly of small size, as shown by the second and third columns of Table 2. There is, however, a significant difference between the overall sample of firms facing a reduction in equity and the sub-sample of them ending in distress: the former are mostly well-capitalized firms. Indeed, their average Equity over Total Assets is 29.68% (i.e., Total Assets that are 3.36 times the level of Equity), quite comparable to the 32.81% average for the whole sample.

In contrast, the sub-sample of firms that end up in distress were already highly indebted even in the absence of the COVID-19 shock, with an Equity-Total Assets ratio of 10.46%. Being highly leveraged to begin with, distressed firms earn an average ROE of 9.11% but an average ROA equal to only 3.57%, i.e., about half the whole sample average. Moreover, also their Cash to Total Assets ratio is about 30% less than the average ratio for the whole sample. Finally, these firms also have a Z-score of 4.43, corresponding to 65% of the average Z-score in the whole sample. Hence, according to our simulation the virus outbreak mostly affected distressed firms that were already significantly less cred-

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itworthy, irrespective of their sector and of the severity of the lockdown. This finding implies that an equity injection bringing these firms back to their pre-COVID-19 shock equity level would still leave them with a low Equity-Total Assets ratio relative to other firms, and hence vulnerable to external shocks. [5] Another important observation is that distressed firms are much more labor intensive than other firms: they have far more employees relative to total assets, and a cost structure where labor costs weigh relatively more in total costs (net of employees' costs). As these are highly labor intensive firms, their demise would imply erosion of economic value and massive redundancies.

Figure 6 also shows that a six-month lockdown would entail a €321 billion drop in aggregate yearly profits, a €259 billion equity shortfall for the whole sample, and a €126 equity shortfall for distressed firms. As shown by the upper panel of Figure 7, a six-month lockdown would force about 33% of firms into financial distress (i.e., more than 26,000 companies in our sample). While such a long lockdown period may be considered unrealistic, a full immediate recovery of economic activity after *three months* (as is assumed in our 3-month lock-down scenario) is also quite unrealistic. As underscored for example by Philip Lane, the ECB's chief economist, "it is likely to take at least *three years* for the Eurozone economy to fully recover from the extraordinary and severe shock of the coronavirus crisis" (emphasis added).[6] In line with this possibility, one could also interpret a longer period of lock-down as capturing a more prolonged period of stress in terms of weaker demand, and thus lower revenues. Note, however, that once the lockdown is lifted, firms may no longer benefit from the same advantages as during the crisis, in terms of reduced workers' payments or lower taxes. From this perspective, the losses produced by our simulations for a six-month lockdown may be underestimated, in particular for highly labor-intensive firms.

Recall that the distress rates shown in Figure 7 are *exclusively* due to the lockdown associated with the COVID-19 shock; absent this shock, no firm would be distressed according to the construction of our sample, which only includes firms with positive book equity. Thus, the results indicate, on the one hand, the presence of a significant

[5] This finding is not unique to Italian firms: the average U.S. firm going into distress after the COVID-19 outbreak already had a junk bond rating (B+) before the outbreak, to be compared with an A rating for the average firm, while those that only experienced only some equity erosion have an A rating. These figures are based on 94 Chapter 11 bankruptcy filings, 2010-2013. Sources: Compustat, Company Filings and S&P. We thank E.Altman for providing us these data.

[6] "Eurozone recovery to take three years, warns ECB's chief economist", Financial Times, 1 May 2020.

fraction of firms that were fragile even before the COVID-19 shock. On the other hand, the COVID-19 shock would have an increasing impact on firms' equity if the lockdown were protracted for several months. In fact, as shown by Figure 6, the equity shortfall grows non-linearly in lockdown duration, especially for distressed companies, even though profits decrease linearly by construction, given our assumption that the impact of the lockdown on profits is uniformly distributed across months. This is especially pronounced for distressed companies: after four months, the predicted equity shortfall for distressed companies is 84 % larger than that required after three months, but it becomes 190 % larger after five months, and 306% larger after six. This is entirely due to the optionality of the equity contract as a consequence of the limited-liability option enjoyed by shareholders.

The equity erosion due to the lockdown can also be gauged by its predicted impact on the leverage distribution of Italian firms. Figure 8 shows the distribution of leverage of all the firms in our sample, at the end of 2018, based on our simulations for a 3-month and a 6-month lockdown scenarios. In the baseline no-shock scenario, based on actual 2018 data, all firms have positive equity (by construction), so that leverage (calculated as Equity over Total assets) ranges from almost zero to 100%, with the median firm featuring a 29% leverage, and firms at the 25^{th} and the 75^{th} featuring 15% and 48%, respectively. In the 3-month lockdown scenario, a significant fraction of firms enters into distress, as shown also by Figure 6. Median leverage drops to 20% and for firms at the 25^{th} and at 75^{th} percentile leverage becomes 4.6% and 40%, respectively. In 6-month lockdown scenario, more than 25% of firms would be in distress, the median firm would become highly indebted with a leverage ratio of 11%, and 75% of firms have a leverage below 27%. Therefore, Figure 8 underscores that there may be a greater fragility of the capital structure of Italian firms following the COVID-19 shock, if public support is given entirely in the form of debt financing or loan guarantees.

The impact of the lockdown is not the same for large, medium and small firms, as illustrated by the lower panel of Figure 7. Small firms appear to be the most fragile, given that in all the lockdown scenarios considered, their distress rate exceeds that for other firms, ranging from 4.7% for a one month lockdown to 33% for six months. The second most affected firms are medium ones, with a distress rate between 3.8% and 27%, while the least affected are large firms, with a distress rate ranging from 0.9% to 15.7%.

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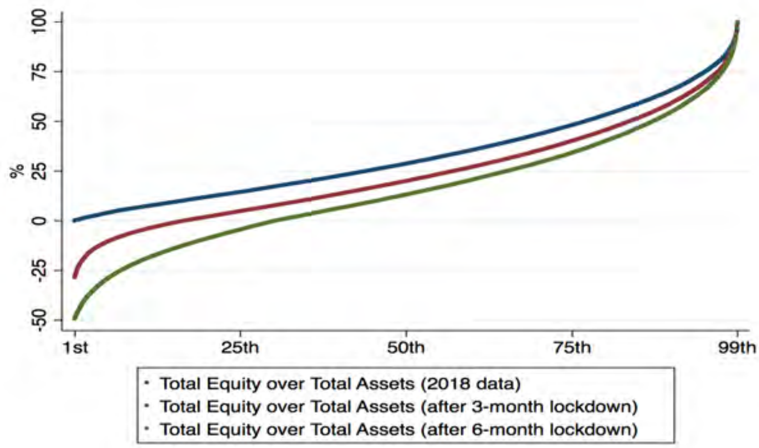
Figure 8: Firms leverage distribution

The figure shows the leverage distribution without the COVID-19 shock, in the 3-months lockdown scenario and in the 6-months lockdown scenario. Leverage is defined as Equity over Total asset ratio. Extreme values have been trimmed. Data source: Orbis (Bureau Van Dijk).



Firm size is not only associated with widely different lockdown-induced default rates, but also with different equity shortfalls, as illustrated by Figures 9, 10 and 11, which respectively refer to large, medium and small firms. Clearly, large companies fare better than medium and small companies, being initially better capitalized. The amount required to recapitalize large distressed companies after a 3-month lockdown is €10 billion, against €10 billion required for medium firms, and €11 billion for small companies, even though the latter two size classes account for a considerably smaller fraction of total assets and employees than large companies, as seen above. This large difference in the equity shortfall across firm size categories partly reflects the fact that the fraction of companies predicted to become distressed (i.e., have negative net worth) in response to the lockdown is larger for small and medium enterprises (SMEs) than for large companies, as shown by the lower panel of Figure 7. In particular, after a three-month lockdown, the default rate is 6.4% for large firms, while it equals 14.3% for medium firms and 18.1% for small firms; after a 6-month lockdown, it is predicted to triple for large firms, and approximately double for SMEs.

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Figure 9: Equity and Profit Shortfall: Large Firms

The figure shows the annual financial projections for large firms, defined as those with more than 250 employees and balance sheet total of more than €43 million. Profit shortfall is defined as the difference between end-of-the-year profits after X months of lockdown and annual net income in 2018. Equity shortfall is defined as the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined as the sum of the firms' negative profits (losses) after X months of lockdown and their initial equity (as of the end of 2017). Data source: Orbis (Bureau Van Dijk).

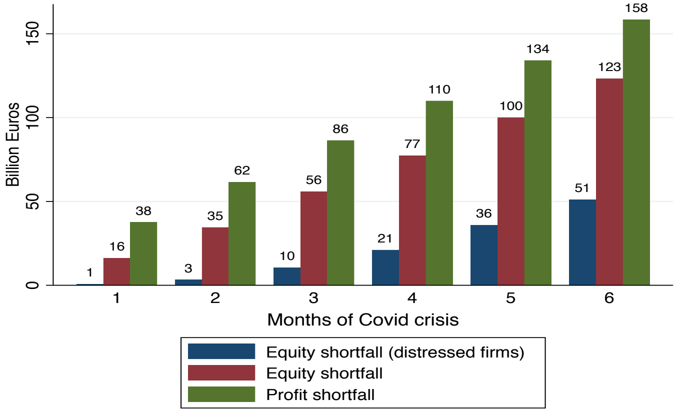


Figure 10: Equity and Profit Shortfall: Medium-Sized Firms

The figure shows the annual financial projections for medium-sized firms, defined as those with between 50 and 250 employees. Profit shortfall is defined as the difference between end-of-the-year profits after X months of lockdown and annual net income in 2018. Equity shortfall is defined as the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall is defined as the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined as the sum of the firms' negative profits (losses) after X months of lockdown and their initial equity (as of the end of 2017). Data source: Orbis (Bureau Van Dijk).

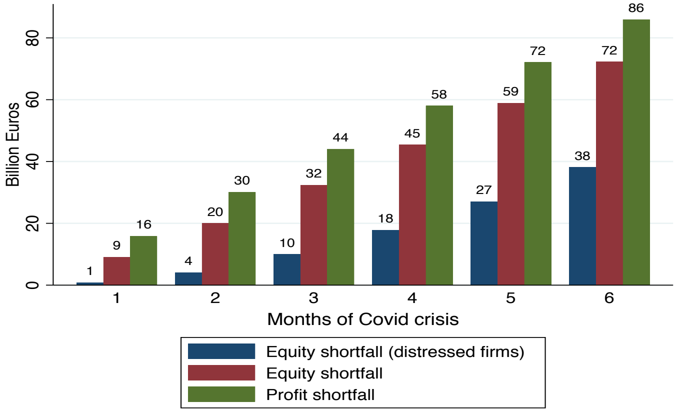
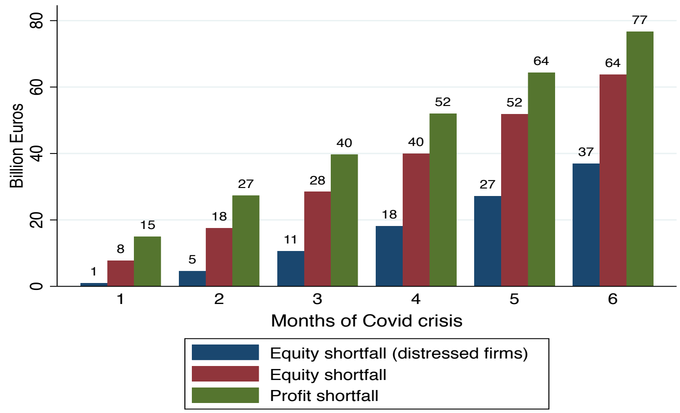


Figure 11: Equity and Profit Shortfall: Small Firms

The figure shows the annual financial projections for small firms, defined as those with less than 50 employees and balance sheet total of more than €2 million. Profit shortfall is defined as the difference between end-of-the-year profits after X months of lockdown and annual net income in 2018. Equity shortfall is defined by the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall is defined as the sum of all firms' end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined as the sum of the firms' negative profits (losses) after X months of lockdown and their initial equity (as of the end of 2017). Data source: Orbis (Bureau Van Dijk).



The characteristics of the firms predicted to enter distress after a three-month lockdown can be inferred from Column 3 of Tables 3, 4 and 5: these firms are much smaller than the others, less profitable, far less capitalized, and closer to insolvency than other firms, even within their respective size class and even relative to all firms projected to make losses (Column 2). In terms of Z-scores, instead, there are no significant differences between firms that suffer an equity shortfall and those that end up in distress. As for the employment consequences of the lockdown, of the 790,905 employees employed by firms that would be in distress, 29% belong to large firms, 40% to medium size firms, and 31% to small firms, suggesting a very different distribution relative to the whole sample shown in Figure 1.

The subsequent figures break down the drop in profits and the equity shortfall by sector and geographical region. Figure 12 shows that the profit drop is concentrated in Manufacturing, Wholesale Trading, and, to a far smaller extent, Construction and Business Services. Importantly, these sectors also happen to be the top four sectors by number of employees.

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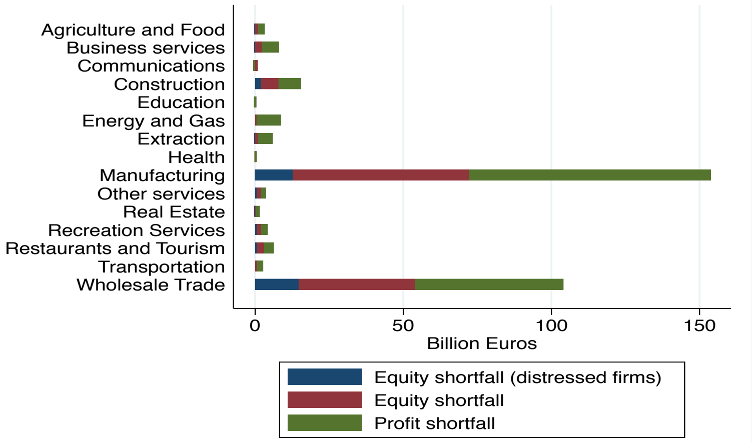
Figure 12: Profit and Equity Shortfall by Sector with a 3-Month Lockdown

The figure shows the annual projections for equity and profit shortfalls by sector. The sector definitions are from national accounting and firm sectoral data as defined by ISTAT. Profit shortfall is defined as the difference between end-of-the-year profits after X months of lockdown and annual net income in 2018. Equity shortfalls is defined by the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall is defined as the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined as the sum of firms' negative profits (losses) after X months of lockdown and their initial equity (as of the end of 2017). Data source: Orbis (Bureau Van Dijk).



Surprisingly, the drop in profits and the equity shortfall in the Recreation Services and Tourism sectors are comparatively small. This is probably because these are labor-intensive sectors with low fixed costs and hence, though severely hit by the lockdown, most of their labor costs during the lockdown are covered by the wage subsidy paid to inactive workers. However, going forward, these sectors may be more affected by social distancing than others and thus be subject to an longer effective lockdown than others. This may outweigh the less severe impact on their profits early in the lockdown months. Moreover, as stressed above, even if the lockdown is severe for the Recreation Services and Restaurant and Tourism sectors (respectively, 74.2% and 62.1%), relatively few firms in our sample belong to these sectors (4.8%), probably due to the prevalence of micro-firms (namely, those with less than 10 employees), which are not included in our sample.

Figure 13 shows that, within Manufacturing, the sub-sectors that suffer the largest drop in profits are Fabricated Metal Products, Industrial and Commercial Machinery and Computer Equipment, and Transportation Equipment. These sub-sectors are also those with the largest equity shortfalls and funding need to revive their distressed firms.

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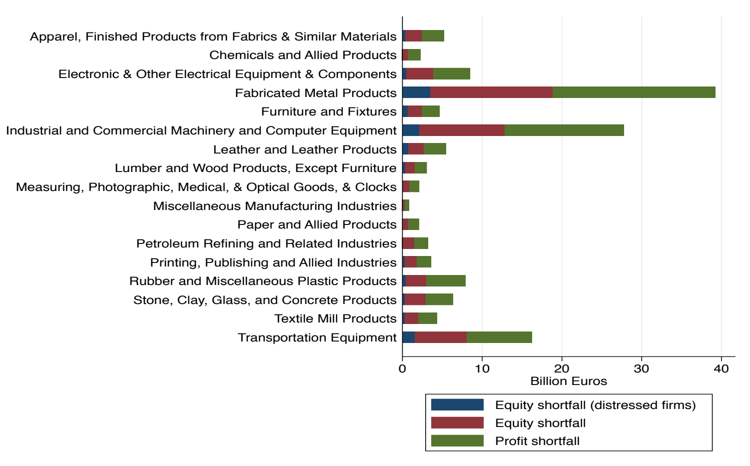
Figure 13: Profit Shortfall by Manufacturing sub-sectors with a 3-Month Lockdown

The figure shows the annual projections for equity and profit shortfalls by sub-sectors of the manufacturing sector. The sector and sub-sector definitions are from national accounting and firm sectoral data as defined by ISTAT. Profit shortfall is defined as the difference between all firms' end-of-the-year profits after 3 months of lockdown and annual net income in 2018. Equity shortfalls is defined by the sum of end-of-the-year negative profits (losses) after 3 months of lockdown. Equity shortfall is defined as the sum of end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined as the sum of firms' negative profits (losses) after X months of lockdown and their initial equity (as of the end of 2017). Data source: Orbis (Bureau Van Dijk).



Finally, Figure 14 shows that most of the profit and equity shortfalls refer to firms located in Northern Italy, in contrast to firms in the South being the lowest. This reflects the geographic distribution of economic activity within the country, rather than the impact of the COVID-19 shock itself, since we model the impact of the lockdown as geographically homogeneous, as it has actually been at least until early May 2020 (the time of this writing). However, the effects of social distancing policies may persist much longer for economic activity in Southern (and to some extent Central) regions, where Tourism and Retail Trade are proportionately more important than Manufacturing and Business Services, and are likely to revert to the pre-crisis activity level much more slowly. Hence, the persistence of the COVID-19 shock may eventually turn out to be greater in the South, and to some extent in the Center, than in the North of the country relative to the current forecast. Our estimates fail to account for this, being predicated on the assumptions that the lockdown will be lifted simultaneously in all sectors and geographical areas, and that economic activity will immediately revert to pre-crisis levels in all of them.

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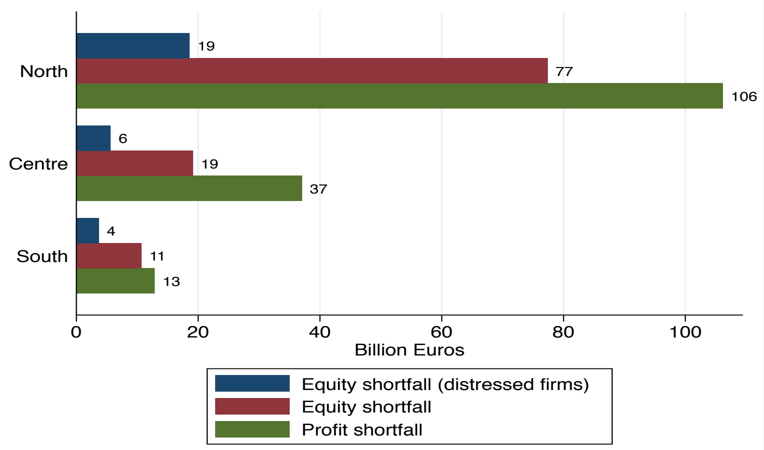
Figure 14: Profit Shortfall by Geographic Area with a 3-Month Lockdown

The figure shows the annual projections for equity and profit shortfalls by geographic area. The geographic area definitions are from national accounting and firm sectoral data as defined by ISTAT. Profit shortfall is defined as the difference between all firms' end-of-the-year profits after 3 months of lockdown and annual net income in 2018. Equity shortfalls is defined by the sum of all firms' end-of-the-year negative profits (losses) after 3 months of lockdown. Equity shortfall is defined as the sum of all firms' end-of-the-year negative profits (losses) after X months of lockdown. Equity shortfall (distressed firms) is defined as the sum of the firms' negative profits (losses) after X months of lockdown and their initial equity (as of the end of 2017), i.e., those firms that end up with negative equity value in 2018, due to the lockdown. Data source: Orbis (Bureau Van Dijk).



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As mentioned above, our simulations also ignore spillover effects among sectors, and the effects of the COVID-19 shock on the demand side, that is, the substantial impact that it is likely to have on consumption, investment and exports.

5 Conclusions

The evidence in this paper shows that the losses inflicted by the COVID-19 shock on Italian firms are likely to produce a sizeable erosion of their equity, to the point that, absent any recapitalization or debt restructuring, 17% of the firms in our representative sample of Italian industry would end up with negative 2020 year-end net worth after a three-month lockdown, based on 2018 data. Importantly, this number represents the distress rate exclusively due to COVID-19. From this perspective, our analysis suggests substantial effects of the virus outbreak in terms of widespread bankruptcies and layoffs and,

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consequently, potential long-term damage to the economic fabric of the country. Public liquidity provisions via debt financing, currently encouraged by the loan guarantees provided by the Italian government, will simply not do: providing more debt to already highly indebted firms is throwing good money after bad, as it will temporarily keep them alive without restoring their solvency.

Addressing the plight of these companies calls for a robust equity injection. To some extent, the most promising of these firms, especially the larger ones, might be able to raise new equity funding on the capital market, and/or bargain with their creditors so as to restructure their debt obligations, and thus rebalance their capital structure, and start to invest again, once the crisis abates. For many others, as underscored by Somerset Webb's and Martin Wolf's quotes at the start of this paper, the government could step in, providing much-needed equity rather than debt finance, as it is currently doing. However, this public intervention raises several additional questions. First, which firms should the government target with its equity injections? Second, how much equity should it provide to each sector, and each firm? Third, what specific contractual form should the equity funding take (voting common equity, non-voting common equity, hybrid instruments such as convertible debt, debt with warrants attached, etc.,)? Fourth, should this equity participation have a predefined time span, and what exit strategies should be envisaged for the government as a shareholder?

The evidence presented in this brief study does not address any of these all-important policy questions, but does hint at a dilemma that the government is likely to face in answering the first two questions in the context of Italy–and possibly also in other countries. The objective of supporting employment begs for equity injections being directed mainly at the companies in distress, not only because these are at the highest risk of ending up in bankruptcy but also because they are the most labor-intensive, so that their liquidation would lead to a greater impact on employment, and the social fabric, generally. However, our data indicate that these are also the firms that already had, by far, the most fragile balance sheets even prior to, and in the absence of, the COVID-19 crisis. Hence, on the one hand, returning them to the equity levels prior to the crisis would not necessarily restore them to good health: such an equity injection risks leaving them still vulnerable to external shocks. On the other hand, providing them with a more generous equity injection would clearly require escalating the funding well beyond the sums implied by our

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projections. One would then have to ask whether such large sums would not be better invested in firms that hold greater promise of growth, profitability, and job creation, even if they may have borne significant losses during the current crisis.

While our analysis presents broad-brush evidence of the impact of the crisis at the levels of sector, firm size, and geographical region, concrete policy interventions would call for a more granular analysis, drilling down to the sub-sector, provincial, or at least regional levels, hence requiring more detailed data. They would also call for more up-to-date firm-level data, at least referring to 2019. Of equal importance, they would require detailed modelling and measurement of supply-chain effects across sectors and demand-side feedback effects. Given how important the resolution of the crisis is for the Italian corporate sector, and indeed the Italian economy, such an effort would be worthwhile.

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Mortality containment vs. economics opening: Optimal policies in a SEIARD model

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We adapt a SEIRD differential model with asymptomatic population and Covid deaths, which we call SEAIRD, to simulate the evolution of COVID-19, and add a control function affecting both the diffusion of the virus and GDP, featuring all direct and indirect containment policies; to model feasibility, the control is assumed to be a piece-wise linear function satisfying additional constraints. We describe the joint dynamics of infection and the economy and discuss the trade-off between production and fatalities. In particular, we carefully study the conditions for the existence of the optimal policy response and its uniqueness. Uniqueness crucially depends on the marginal rate of substitution between the statistical value of a human life and GDP; we show an example with a phase transition: above a certain threshold, there is a unique optimal containment policy; below the threshold, it is optimal to abstain from any containment; and at the threshold itself there are two optimal policies. We then explore and evaluate various profiles of various control policies dependent on a small number of parameters.

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1. Introduction

A COVID-19 outbreak has begun in China at the end of 2019 [HWO, 2020], later spreading to most other countries and causing a large number of infected individuals and deaths. In Italy, the first country to be hit after China, the first confirmed autochthonous case was recorded on February 21, and the first death on February 22 [Statista, 2020]; the first death in US was recorded on February 28th [Times, 2020].[1] The outbreak has so far caused at least 4 million recorded cases, and $275,000$ recorded deaths [Worldometer, 2020], with real numbers estimated at much higher values. In New York City there have been at this time at least $27,000$ deaths, corresponding to 0.335% of the population. Massive regulatory responses have been put in place by most local and central governments, imposing restrictions (that we call lockdown hereafter) on travels and individual freedom. By several measures, the lockdowns have reduced the spread of the virus and the potential mortality. On the other hand, the intensity of the impact of the pandemic, the lockdown policies, and the behavioral response of agents beyond the regulations (spontaneous social distancing, etc.), have greatly impacted the economic production. As of May 7, 2020, the IMF economic projection predict a loss in real GDP in 2020 of 3% worldwide, as opposed to +3.45% in the four years before (2016-2019). Even with the IMF forecast for the rebound of 5.8% in 2021, the cumulated loss relative over the next two years *relative to the trend* would be about 4% of World GDP. In the advanced economies, this loss would be 5.65%, including 6.85% in the European Union and 5.8% in the United States, and lower numbers in Asia and Pacific (-3.35%) or Sub-Saharan Africa (-2.9%). These are massive numbers, quite different by areas of the world, and updated regularly with likely higher GDP losses.

It is imperative for most regulatory bodies to balance between the containment of the effects of the outbreak, and the economic impact of the regulatory measures. In this paper we adopt the number of COVID-19 fatalities and the total GDP as proxies for the two effects, and provide a framework to think about costs and benefits. The two indicators have been selected for their reliability: GDP is a standard economic indicator, while mortality, in particular total mortality and its comparison with the expected mortality from previous years, is regularly monitored and made public in many countries. These assumptions allow to determine optimal lockdown policies using optimal control theory.

More specifically, we consider a proxy for containment policies that encompasses the entire set of behavioral responses of agents who reduce consumption, the shut-down of markets themselves and measures that limit people's movements, thus reducing the chances of infection and the availability of labor. We then introduce the cost of a Covid related death for the social planner; for each intervention policy tuned by a control function, we estimate a loss functional combining total Covid related fatalities and overall production loss in a given time frame.

The evolution of the epidemics is then described by a SEAIRD ordinary differential equations model, as specified in Section 3.1 where a sizeable fraction of the population are asymptomatic individuals who can contaminate others. At each time t, the lockdown is measured by an opening level of society (economic activity and social contacts) $c(t) \in [0, 1]$, $c = 1$ being absence of any restriction and $c = 0$ being the complete shutdown of all activities.[2]

Many papers in the recent literature, including [Grigorieva et al., 2020] and various economic papers cited in Section 2.1 below, compute the optimal policy in a general class with only technical restrictions on the policy space; but this contrast with feasibility of the restriction policies, which cannot adjust continuously: more realistically [Yan and Zou, 2008], restriction measures require a short time to be implemented, and then should be kept constant for a certain time. For these

[1] These are the officially recorded dates, and the virus might have been spreading before these times; we record them here as references for the actual dates we will use in simulations.

[2] As a normalization, c will be assumed to linearly affect the infection rate and has a concave effect on GDP, see infra.

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reasons, we drastically reduce the dimensionality of the policy space, by taking controls which are constant for some minimal period $\overline{\delta}$, and then transition linearly to the next level in time $\underline{\delta}$.

The main point of our study is that one can find the various opening levels that avert a sizeable number of deaths without determining an excessive damage to the economy: Figure 1 illustrates the potentials of this analysis, in that deviations from the best policies either cause an excessive economic loss for a residual decrease in death rate, or an undesirably high mortality to prevent a rather minor decrease in GDP. See for instance [Kaplan et al., 2020] for a similar assessment of the trade-offs involved, implicit or explicit in most economic works discussed in next Section. The darker blue curve in Figure 1 reflects the constrained relation between mortality and GDP for different values of the control policy and can be thought as a technical rate of transformation. As we will explain later, it is generally preferable to be closer to the origin. A social welfare function and its indifference curves as in the light blue curve defines an optimal rule - when it exists. Its slope reflects the marginal rate of substitution (MRS) between mortality reduction and GDP losses and under simplifying assumptions, is the inverse of the statistical value of life, as we will explain later.

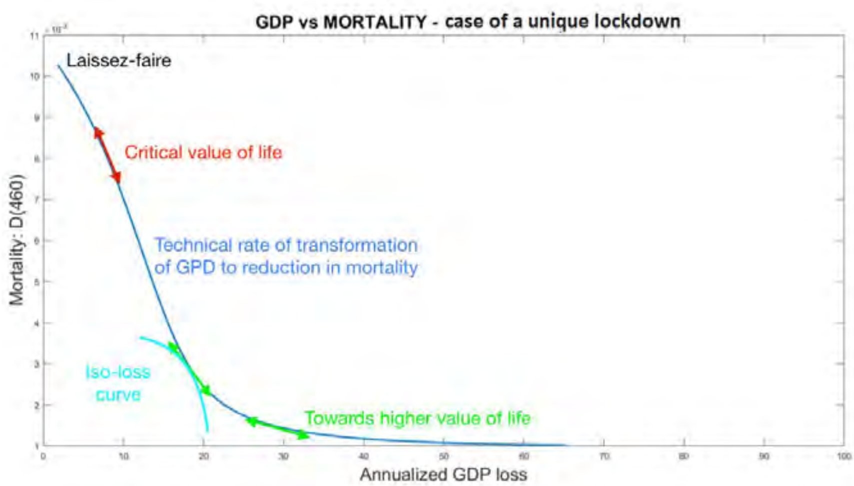

FIGURE 1. Mortality and production loss with one single, long lasting lockdown. The optimal choice, see Section 6.2, reduces mortality to 0.26% with a 19.45% GDP loss: the lockdown realizes a sharp containment of mortality, but the constraint of protracted measures causes a dramatic GDP loss. This policy has not been followed by any country.

Figure 1 also suggests that, for some values of the preferred MRS, there could be two tangency points determining a transition of phases, and possible non-uniqueness of solutions. In Section 5.3, we show one simple example of this phenomenon, and argue that it is the effect of a transition

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of phases in which the optimal control passes from being the absence of any containment, to a more substantial tightening as function of the social cost of COVID-19 deaths a. As a result, at a critical value of a there is coexistence of two optimal controls generating the same value of the loss functional. In addition, the multiplicity of suboptimal controls around the critical value of a, can have relevant social consequences in terms on how to evaluate potential alternatives to a given containment policy. We then argue that, in general, the optimal control is likely to be unique provided that the social cost of COVID-19 mortality is large enough.

We finally consider some examples. Parameters are realistically taken from current observations, and validated by reproducing observed jump in mortality to this day, and GDP reductions due to first lockdown periods. In the examples, we restrict, as mentioned, to simple controls in low dimensional spaces: in the first example, a unique lockdown is imposed at Day 85 till the end of the observed period, a possibility that only few countries (such as Sweden, for instance) seem to have considered; with our choice of time frame, Day 85 corresponds to March 25: as detailed in Section 6.1, this is about when most lockdowns started; in the second example, a partial reopening is realized at Day 120, after a drastic initial lockdown has been imposed between Day 85 and Day 120, a typical situation at the current moment in time in many countries; in the third example, a periodic alternation of lockdowns and reopenings is applied. In the last example, the optimal control leads to herd immunity, which is achieved in such a way as to have very few infected at the time in which the immunity is reached; the optimization has automatically determined the best possible access to herd immunity [Moll, 2020]. All examples are explicitly simulated and optimal controls are numerically determined. We then carry out a sensitivity analysis to evaluate the sensitivity of the results to errors and fluctuations in parameter selection.

2. Previous works and limitations

2.1. **Brief literature review.** The number of papers adapting the SIR model to various economic contexts is large and rapidly evolving and it is impossible to make justice to the literature.

[Jones et al., 2020] derive an optimal strategy where the social planner can affect both the contacts from consumption and contacts from production, each of them contributing to a third on the diffusion parameter β. They study the optimal policy using a standard growth model with leisure-consumption trade-offs. Agents react too little to the epidemics because they do not contemplate the impact of their behavior on other agents' infection rate and a lockdown seriously reduce infection and fatalities in flattening the curve, and avoid congestion of ICU units that would increase the fatality rate.

[Eichenbaum et al., 2020] study a standard DSGE model with a SIR contagion. They find that the epidemic causes *per se* a moderate recession, with aggregate consumption falling down by 0.7% within the year. Optimal containment would lead to a more drastic loss in consumption by 22%. They also discuss the model with various health policies including vaccines, preparedness and other dimensions.

[Acemoglu et al., 2020] develop a multi-SIR model with infection, hospitalization and fatality rate depend on age, with three classes of individuals (young, middle-aged and old). They find that targeted containment policies are most efficient. For the same loss in GDP (-24%), the targeted policies reduce mortality by 0.7 to 1.8 percentage points. They also include a stochastic vaccine arrival, not known for sure by the policy maker, and the stochastic process evolves over time. They assume as in [Alvarez et al., 2020] that full lockdown is not feasible, as we also assume. In [Alvarez et al., 2020] have a SIR model embedded in the growth model. Their optimal policy is to implement a severe lockdown 2 weeks after 1% of the population is infected, to cover 60% of the population, and then gradually reduce the intensity of the lockdown to 20% of the population after 3 months. The absence of testing reduces the welfare. With testing and under the optimal policy, the welfare loss is equivalent to 2% of GDP. Another paper on sequential lockdown with

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heterogeneous population is [Rampini, 2020]. In particular, he uses a fatality rate of 0.06-0.08% for younger agents and 2.67 to 3.65% for older workers.

[Hall et al., 2020] study a variant with the minimization of an objective function and Hamilton-Jacobi-Bellman. Basing their fatality rate on 0.8%from the Imperial college study, they argue that the optimal decline in consumption is approximately 1/3rd for one year. They then consider more recent estimates of the fatality rate, around 0.3% across age groups, and argue that the optimal decline in consumption is still around 18%. Our numbers are in line with these numbers.

[Gollier, 2020b], similar to us assumes that a vaccine is ready after a few months (52 weeks in his case). He uses a R_0 around 2 (1.85 on the slides available on line) prior to containment, and the containment policy drives it down to 1, as we do. He uses a value of statistical life of 1 million euros and studies confinement scenarii under notably periodic reinfection rates. In [Gollier, 2020c, Gollier, 2020a], he further explore the ethics of herd immunity and elaborate on lockdowns differentiated by age groups. In particular, he uses (Table 4 of [Gollier, 2020c]) a valuation of statistical lives depending on age, with the population between 60 and 69 representing 37% of that of individuals below 19, the population between 70 and 79 representing 23% and those above 80% being slightly less than 10% of that maximum value. He further discusses the critical moral hazard issues associated with the epidemic.

Economic consequences associated with demand and transmission mechanisms have been studied in [Guerrieri et al., 2020]: they show that in the presence of multi-sector production, with or without imperfect insurance, it is possible and plausible to have demand shocks in the second round going beyond the initial supply (shutdown shock). They study various aspects such as. labor hoarding and bankruptcy cascades. [Gregory et al., 2020] study the response of the economy in a search framework. The existence of search frictions slows down the recovery, and under reasonable parameter values, the initial lockdown strategy is likely to have long-lasting effects. In their baseline scenario, unemployment increases by 12 percentage points of the labor force for a year, and it takes 4 years to get back to 3 percentage points above the starting point before the lockdown. They find, interestingly, that it is better to have a longer initial lockdown (6 months) and no uncertainty that a shorter lockdown with the risk during 9 to 12 months to face a second lockdown. [Farboodi et al., 2020] estimate a SIR model in which the decline in activity comes from the optimal response of agents without intervention, and where immediate distancing in a discontinuous way, until a treatment is found, is a superior policy, to contain the reproduction number. In contrast, [Krueger and Uhlig, 2020] calibrate a model similar to [Eichenbaum et al., 2020] in introducing goods that can be consumed at home rather than in public places and show that a Swedish-type policy of no-lockdown but strong behavioral response by agents reduces the socio-economic costs of Covid by up to 80%.

Last and most related to us, [Garibaldi et al., 2020] analyze the existence of a SIR-matching decentralized equilibrium and analyze the inefficiencies stemming from matching externalities to determine the optimal way to reach herd immunity.

To conclude, in most of the papers cited above, there is an explicit focus on the optimal policy and the difference between the laissez-faire and the optimal policy is important, due to the externality of contagion. What our paper adds is a formal treatment of existence and a discussion of the potential multiplicity of solution and phase transition due to the non-linearity in the transmission mechanisms of the epidemic. Another paper in this spirit by [Łukasz, 2020] finds explicit optimal solutions in a set of constrained policy functions and characterizes in particular the optimal starting date of the lockdown and discusses time-consistency issues.

2.2. **Limitations.** Our results are only a first indication of a modeling methodology for the search of an optimal trade off between containment of fatalities and reduced loss in welfare. While the parameters of the SEAIR model are related to the current outbreak, a more detailed model needs to consider stratified and geographically dispersed populations, and more elaborate lockdown policies,

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targeted to regions, industries and population that are more at risk. The following points are in order.

(1) As discussed above, several papers have recently addressed similar questions, with in particular a focus on the optimal lockdown policy in the presence of behavioral response of agents on production, on investment or in consumption, of heterogeneity of the population and on learning on the underlying parameters of the economy. Here, as usual in most current literature on COVID-19, we use an extension of the SIR model, hence assuming that each individual has the same chance of meeting every other individual in the population.[3] More realistically, one would need to consider geographically dispersed populations with long range interactions and communities (in the spirit of [Gandolfi and Cecconi, 2016] for instance).

(2) In this paper, in order to have an accurate model of the dynamics of the pandemic with several classes (susceptible, exposed, asymptomatic, symptomatic, recovered, fatality, natural demographic turnover), and yet be able to prove existence and discuss conditions for uniqueness of an optimal response function, we treat the simpler case where the social planner can directly control the contagion parameter with an instrument that also affects GDP, either influencing the behavior of agents or closing markets.

(3) The simulations we provide are based on parameters known at the time of this study, which are also the parameters perceived by policy makers at the time of decision making. With these parameters, we find that the statistical value of a human life that lead to the application of observed levels of lock down is in line with the value employed in actuarial sciences.

(4) Given the nature of the virus and its novelty, there is some uncertainty surrounding the parameters, and these are likely to evolve as medical and epidemiological research progresses. The final numbers will only be available gradually, with large testings currently being implemented. Our approach will therefore only allow us to reassess current policies retrospectively, in one way or another, when the uncertainty at the time of decisions will have dissipated.

(5) Similarly, the parameters connecting the spread of the diffusion of the virus to the loss of GDP from lockdown are uncertain. We choose a median way in the numbers in our simulations.

(6) We remain agnostic in our conclusions and provide sensitivity analysis in describing a range of alternative parameters. The shape of the optimal response in time is relatively invariant to those parameters, but warn that the intensity of the optimal lockdown relies a lot on exact numbers chosen in our simulations.

(7) On the economic side, one dimension not analyzed yet is the fact that the loss of GDP - a supply shock here - is likely to produce second round demand effects, leading to a persistence in the recession that our model does not take into account. Another limitation, of a similar spirit, is the ability of the lockdown to be reversible in the short-run, that is, once stopped, assembly lines may need a lag to resume.

(8) Another limitation in the benchmark exercise is that the fatality rates vary enormously by age and morbidity, and in particular, the fatality rate is 10 times higher at least between the population below 60 and above 60. Since the lockdown mostly acts through adjustment of the labor force in our model, more analysis is needed to draw consequences about the overall lockdown strategy. We cannot deliver conclusions about the opportunity of the observed lockdown.

(9) Another limitation is that our model does not focus on the behavioral response of agents who may have learned about the parameters of the diffusion of the epidemics and reduced

[3]This is a very limiting assumption, and can be well approximated only by small communities. However, this assumption can also be seen as the equivalent of macroeconomic model with a representative agent. The parameters reflecting the aggregate behavior are not necessarily the parameters of the underlying individual agents, but are adjusted to fit the aggregate data in the best. This is a very similar discussion to that in [Keane and Rogerson, 2012] regarding labor supply elasticities.

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the infectivity of the virus independently of the lockdown. We do however believe that there are behavioral responses, but as in [Jones et al., 2020], we also believe that there are strong externalities in the contagion process that the purely-selfish individual behavior would not internalize. In that sense, the non-behavioral approach we follow is a proxy for the inefficiency of the decentralized equilibrium approach that leads to excessive contamination of the population. Future work should however relax the lack of behavioral response and investigate the size and sign of the interaction between government regulations and individual responses.

(10) Last but not least, contrary to other studies, we limit our welfare analysis to a fixed period if time of the pandemic, one year and one quarter in the simulations. The implicit assumption is that after one year, treatments will have improved and vaccines may be possible. This acts as an extreme capitalization effect: in the future, technology will have improved and this is already integrated in economic calculation of the present time. It is easy to do a sensitivity analysis where the length of time periods is augmented, and investigate whether a new cycle of pandemic and lockdown is needed. The solution we exhibit for the optimal lockdown are therefore useful not only to rationalize the current experience, but also to prepare to the next wave or the next virus. We however introduce this assumption of a fixed and short period of time over which the smoothing occurs because the hope of a vaccine was present in public discussion.[4]

In Appendix, we present optimal control problems that would address some of these limitations.

3. A simple SEAIRD model with containment

3.1. **Epidemic model.** We consider SEAIRD, a version of the SIR model ([Chowell et al., 2009] (25) Page 20), with some realistic features taken from current observations of the Covid-19 outbreak. The population is divided into: susceptible (S), exposed (E), asymptomatic (A), infected (I), recovered (R), Covid related deceased (D), and natural deaths (ND). Variables are normalized so that $S + E + A + I + R + D = 1$. Overall, we consider a natural death rate n. This is compensated by a natural birth rate, that can be considered as the rate of inclusion into the labor force; the natural birth rate is reduced by a factor that can be interpreted as a Covid related slowdown.

We assume that affected individuals become first exposed (E), a phase in which they have contracted the virus and are contagious, without showing symptoms. Exposed individuals either develop symptoms at a constant rate $\epsilon\kappa$, becoming infected, or progress into being asymptomatic till healing with rate $(1-\epsilon)\kappa$. A susceptible individual is assumed to have a uniform probability of encountering every exposed and asymptomatic, and has a probability of coming in contact with an infected severely reduced by a factor $s < 1$. The parameter s can be thought of as measuring the effect of an isolation policy that has *per se* no direct effect on the labor force able to participate in economic production. Instead, the probability of all encounters is then affected by the mitigation policies via a factor $c(t)$, that will affect economic activity, as discussed in the next section. Upon encounter, there is a rate β of transmission.

Those who are infected recover at rate γ, or do not recover and die at rate δ; δ/γ is the deaths to recovered ratio to be estimated from current available observations. Asymptomatic recover at rate γ.

[4] As an example, the BBC reported on May 19, 2020 that the US company Moderna had been successful in training the immune system in human. The announcement lead to a 30% increase int he value of this company in the stock markets. See https://www.bbc.com/news/health-52677203

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$$\text{(1)} \qquad \text{Susceptible:} \quad \frac{dS}{dt} = -\beta Sc(t)(sI + E + A) - nS + n(1-D)$$

$$\text{(2)} \qquad \text{Exposed:} \quad \frac{dE}{dt} = \beta c(t)S(sI + E + A) - (\kappa + n)E$$

$$\text{(3)} \qquad \text{Asymptomatic:} \quad \frac{dA}{dt} = (1-\epsilon)\kappa E - (\gamma + n)A$$

$$\text{(4)} \qquad \text{Infected:} \quad \frac{dI}{dt} = \epsilon\kappa E - (\gamma + \delta + n)I$$

$$\text{(5)} \qquad \text{Recovered:} \quad \frac{dR}{dt} = \gamma(A + I) - nR$$

$$\text{(6)} \qquad \text{Covid deceased:} \quad \frac{dD}{dt} = \delta I$$

$$\text{(7)} \qquad \text{Natural deaths:} \quad \frac{dD_N}{dt} = n(S + E + A + I + R)$$

The initial population at the onset of the outbreak of a previously unknown virus consists primarily of susceptible, $S(0) \approx 1$, and a small fraction of exposed, so that $S(0) + E(0) = 1$. For the model under consideration the reproduction number has the following expression

$$\begin{aligned} \mathcal{R}(t) &= \beta S(t)c(t)\left(\frac{1}{\kappa+n} + \frac{\kappa}{\kappa+n}\frac{(1-\epsilon)}{\gamma+n} + \frac{\kappa}{\kappa+n}\frac{s\epsilon}{\gamma+\delta+n}\right) \\ &= c(t)S(t)\frac{\beta\kappa}{\kappa+n}\left(\frac{1}{\kappa} + \frac{(1-\epsilon)}{\gamma+n} + \frac{s\epsilon}{\gamma+\delta+n}\right) \qquad (8) \end{aligned}$$

with basic reproduction number $\mathcal{R}_0 = \mathcal{R}(0)$. Notice that the population $S + E + A + I + R + D$ is preserved. This is a consequence of the fact that by including the term n demography replaces all deaths except Covid deaths.[5]

3.2. **Containment policies.** Containment policies are aimed at reducing the spread of the epidemic by reducing the chances of contacts among individuals. This is reflected in the model by a coefficient $c(t)$ that modulates the encounters between susceptible and either exposed, infected or asymptomatic individuals. We assume that the reduction is the same for all groups, as we have already included the effect of symptoms in segregating infected individuals. This justifies the factor $c(t)$ in (1).

The opening level function $c(t)$ takes values in $[c_0, 1]$ $c_0 > 0$; $c(t) = 1$ indicates that there is full opening, and no lockdown measures have been taken, this is, by default, the status at the early stages of the outbreak. The lower bound c_0 corresponds to the infeasibility of a complete shutdown; this features the fact that there will always be a minimum amount of productive activity (e.g. via internet for home production) from private agents that cannot be interrupted. Provided c_0 is small enough, all our results are insensitive to the precise value. Further, to model concrete feasibility of the policy, the control is assumed to be a continuous, piece-wise linear function, with the additional constraints of being constant for long enough time intervals $\overline{\delta}$; the transitions between the various constant levels are taken to be linear and last at least some $\underline{\delta}$ to model non-negligible friction in policies implementation; the controls are then Lipschitz[6] continuous. The detailed form of $c(t)$ is given in Section 5.1; and several examples are presented in the Section 6.

[5] Mathematically, this is easily seen by taking the derivative of $S + E + A + I + R + D$. In fact, letting $\phi = S + E + A + I + R + D$, we have that $\phi(0) = 1$ and $\frac{d\phi}{dt} = \frac{d(\phi-1)}{dt} = -n(\phi - 1)$, so that, since $(\phi - 1)(0) = 0$, necessarily $\phi \equiv 1$ by uniqueness of solutions of differential equations.

[6] A function f is Lipschitz continuous with Lipschitz constant M on an interval $[a, b]$ if there exists a constant M such that $\frac{|f(x)-f(y)|}{|x-y|} \leq M$ for any $x, y \in [a, b], x \neq y$.

8

The class of containment policies considered in this work is in sharp contrast with other choices, such as [Grigorieva et al., 2020], in which all continuous functions are considered as possible controls. Our work is in the spirit of other applied papers [Rahimov and Ashrafova, 2010], focused on more realizable controls.

4. Economic effects of epidemic and lockdown

4.1. **Social planner's objective.** We investigate optimal containment policies balancing the effect of overall death vs. loss of production. This includes an a-priori evaluation of the social cost of Covid deaths, embodied in a constant a. The social planner's loss functional (the negative of its utility) $\mathcal{W}$ combines production P and the number of new deaths from Covid [7] $D'(t)$, as follows: $\mathcal{W} = -\frac{P^{1-\sigma}}{1-\sigma} - aD'(t)$. The social planner minimizes a loss function between an initial period $t_0 = 0$ and a final period $t_1 = T$ which could be infinity:

$$\mathcal{L} = \left\{ \int_0^T e^{-rt} \left[\mathcal{V}(P(t)) + aD'(t) \right] dt \right\}$$

where $\mathcal{V}(P(t))$ is a decreasing convex function of the GDP $P(t)$, and a is the cost of a covid death $D(t)$ for the social planner. The social planner discounts the future at rate r; such discount factor incorporates both the lesser interest for more distant economic consequences and the preference for containing immediate deaths, hence it acts in the direction of flattening the infection curve. Further normalizing the full-capacity GDP to 1, and assuming that the loss function is zero for full capacity, a typical function would be:

$$\mathcal{V}(P) = -\frac{P^{1-\sigma} - 1}{1-\sigma}$$

with $\sigma > 0, \sigma \neq 1$, and $\mathcal{V}(P) = -\log(P)$ if $\sigma = 1$. For values of σ above 1 (our choice hereafter will be 2),

$$\lim_{P \to 0} \mathcal{V}(P) = -\infty;$$

it follows that $c = 0$ is never reached, and this further justifies the assumption of $c \geq c_0$. We have

$$\mathcal{V}'(P) = -P^{-\sigma}$$
$$\mathcal{V}\text{"}(P) = \sigma P^{-\sigma-1} > 0$$

As a last remark, with a linear loss function $\sigma = 0$, the parameter a can directly be interpreted as the value of life in elasticity with respect to GDP. With higher values of σ, the value of a relates to the value of life in marginal utility of GDP, given the aversion to intertemporal fluctuations in GDP that is characterized by the elasticity of intertemporal substitution introduced in the next section.

4.2. **Production and welfare.** We take the overall production P to be a linear function of labor. At any given time, the labor force is $S + E + A + R$, but its effective availability for production is determined by the current opening policy $c(t)$. The link between $c(t)$ and GDP is captured by a function

$$\mathcal{G}(c(t))$$

[7] An interesting question is whether the social planner should also consider the change in natural deaths due to a decreasing population, a reduction of traffic accidents and an increased risk for untreated pathologies caused by the lockdown and the outbreak itself. We do not address this important question here.

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and it affects GDP as:

$$P(t) = \mathcal{G}(c(t))L(t) \tag{9}$$
$$= \mathcal{G}(c(t))\,[S + E + A + R]\,. \tag{10}$$

Labor availability in the presence of a lock down is not assumed to be linear, as the effects of socio-economic restrictions can be contained by work force substitution or increased productivity. We assume an iso-elastic control

$$\mathcal{G}(c(t)) = c(t)^{\theta} \tag{11}$$

with $\theta \in (0, 1)$ for reasons discussed in the parameter selection section 6.1. We think of θ as a reduced form parameter that connects the infection spread and the change in GDP.

With these assumptions, the loss function becomes

$$\mathcal{L} = \left\{ \int_0^T e^{-rt} \left[-\frac{(c(t)^{\theta}\,[S + E + A + R])^{1-\sigma} - 1}{1 - \sigma} + aD'(t) \right] dt \right\}. \tag{12}$$

5. Mathematical results

5.1. **Existence of a global minimum of the loss functional.** In this section we prove the existence of a global minimum over a suitable class of control functions c. More precisely, fix two values $\overline{\delta}, \underline{\delta}$ with $\overline{\delta} > 2\underline{\delta} > 0$, and let $\mathcal{K}$ be the collection of continuous functions

$$c : [0, T] \to [c_0, 1],$$

such that there exist $\alpha_1 < \cdots < \alpha_{k-1} \in [0, T]$ and $c_0 \le \beta_1, \ldots, \beta_k \le 1$, with $\alpha_{i+1} - \alpha_i \ge \overline{\delta}$ for all $i = 1, \ldots, k-1$, such that $c(t)$ is continuous and

$$c(t) = \begin{cases} \beta_1 & \text{if } t \in [0, \alpha_1] \\ \beta_i & \text{if } t \in [\alpha_{i-1} + \underline{\delta}, \alpha_i], \quad i = 1, \ldots, k \\ \beta_i + (\beta_{i+1} - \beta_i)(t - \alpha_i)/\underline{\delta} & \text{if } t \in [\alpha_i, \alpha_i + \underline{\delta}], \end{cases} \tag{13}$$

where we have taken $\alpha_0 = 0, \alpha_k = T$. Notice that $\mathcal{K}$ is a class of Lipschitz continuous functions with Lipschitz constant bounded uniformly by $(1 - c_0)/\underline{\delta}$ on $[0, T]$, as examplified in Figure 2.

Theorem 5.1. *$\mathcal{K}$ is relatively compact in the space of continuous functions $C[0, T]$.*

Proof. For each sequence $\{c_n\}, c_n \in \mathcal{K}$, we have $c_n \le 1$ and $|c_n(x) - c_n(y)| \le (1 - c_0)|x - y|$; by Ascoli-Arzela Theorem, the sequence converges uniformly in $[0, T]$, possibly up the a subsequence, to a continuous function c. Clearly the function c has range in $[c_0, 1]$ and is Lipschitz continuous with Lipschitz constant bounded by $(1 - c_0)/\underline{\delta}$. Let us prove that it must be piece-wise linear of the form (13).

Consider $\eta \le \underline{\delta}$ and points of the form $x_k = k\eta$ for $k = 1, \ldots, \lfloor T/\eta \rfloor$. Take k_1 and k_2 such that $|k_1 - k_2| < \underline{\delta}/\eta$. We consider the two possible cases.

(1) Suppose $c(x_{k_1}) = c(x_{k_2})$. Since $|x_{k_1} - x_{k_2}| < \underline{\delta}$, any c_n has the extreme values of the interval $[x_{k_1}, x_{k_2}]$ exactly at x_{k_1} and x_{k_2}; for small ϵ and large enough n, assuming, without loss of generality, that $c_n(x_{k_1}) \le c_n(x_{k_2})$, we have

$$c(x_{k_1}) - \epsilon \le c_n(x_{k_1}) \le c_n(x) \le c_n(x_{k_2}) \le c(x_{k_2}) + \epsilon = c(x_{k_1}) + \epsilon$$

for all $x \in [x_{k_1}, x_{k_2}]$. Hence, in the limit for $n \to \infty$, we have $c(x) = c(x_{k_1})$ for all $x \in [x_{k_1}, x_{k_2}]$.

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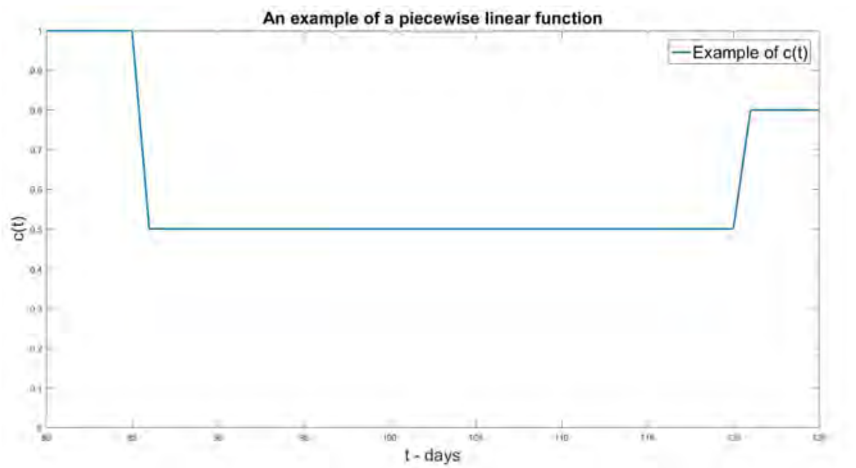

FIGURE 2. An example of the control variables c used as allowed opening levels. Notice that we always consider controls of this type, although in the figures presented in later sections the linear, non costant, portions might not be easily detectable.

(2) If $c(x_{k_1}) \neq c(x_{k_2})$, then take $x_{k_2} + \underline{\delta}$ and $x_{k_2} + \underline{\delta} + (\overline{\delta} - \underline{\delta})/2$: it must be $c(x_{k_2} + \underline{\delta}) = c(x_{k_2} + \underline{\delta} + (\overline{\delta} - \underline{\delta})/2)$; in fact, for $\epsilon < |c(x_{k_1}) - c(x_{k_2})|/3$ and n large enough, $|c_n(x_{k_1}) - c_n(x_{k_2})| > |c(x_{k_1}) - c(x_{k_2})|/3 > 0$, hence c_n must have a non constant part in $[x_{k_1}, x_{k_2}]$ and must thus be constant in $[x_{k_2} + \underline{\delta}, x_{k_2} + \underline{\delta} + (\overline{\delta} - \underline{\delta})/2]$. For the same reason, $c(x_{k_1} - \underline{\delta}) = c(x_{k_1} - \underline{\delta} - (\overline{\delta} - \underline{\delta})/2)$. Consider the sup $\overline{x}_1$ of the points $x \leq x_{k_2}$ such that $c(x) = c(x_{k_1} - \underline{\delta})$, and the inf $\overline{x}_2$ of the points $x \geq x_{k_1}$ such that $c(x) = c(x_{k_2} + \underline{\delta})$. For ϵ and n large enough, c_n must be constant outside of $[\overline{x}_1 - \epsilon, \overline{x}_2 + \epsilon]$, and linear in some interval of length $\underline{\delta}$ included in $[\overline{x}_1 - \epsilon, \overline{x}_2 + \epsilon]$, connecting two values at distance at most ϵ from $c(\overline{x}_1)$ and $c(\overline{x}_2)$, respectively. Since this holds for all small ϵ, it implies that $|\overline{x}_1 - \overline{x}_2| = \underline{\delta}$, and that c must be linear in between these points, connecting $c(\overline{x}_1)$ and $c(\overline{x}_2)$ by continuity.

Pairs of points in which (2) happens cannot overlap, hence indicate by $\alpha_1, \alpha_2, \ldots, \alpha_{k-1}$ be the smallest points of each pair, arranged in increasing order; let $\alpha_0 = 0, \alpha_k = T$; and let $c_0 \leq \beta_1, \ldots, \beta_k \leq 1$ be the such that $c(x) = \beta_i$ for $x \in [\alpha_{i-1} + \underline{\delta}, \alpha_i]$ for $i = 1, \ldots, k$. We have shown that $c(x)$ satisfies (13) for these values of α's and β's. This finishes the proof.

□

Consider now the following minimization problem

$$\min_{c \in \mathcal{K}} \mathcal{L}(c)$$

with $\mathcal{L}$ as in (12). We now show that the functional is continuous in c: once this is proved, by Weierstrass Theorem we conclude that a global minimum $c* \in \mathcal{K}$ of the functional $\mathcal{L}$ exists. To prove continuity we use the well-posedness of the S-E-A-I-R-D model. In fact, let $\vec{X} = (S, E, A, I, R, D)$ and denote by $\vec{F}(c, \vec{X})$ the vector-valued function having as components the right-hand sides of the S-E-A-I-R-D differential equations.

Then we can rewrite the system in vector form

$$\vec{X}' = \vec{F}(c, \vec{X}), \ \ \vec{X}(0) = \vec{X}^0.$$

where by assumption the norm[8] of the solution $\vec{X}$ is such that $\|\vec{X}\| \leq 1$ and $\vec{F}$ is smooth in both variables. Let now $c_n \in \mathcal{K}$ such that c_n converges uniformly in $[0, T]$ to a function $c \in \mathcal{K}$. Consider now the solution $\vec{X}_n \in C^1[0, T]$ of

$$\vec{X}' = \vec{F}(c_n, \vec{X}), \ \ \vec{X}(0) = \vec{X}^0$$

and denote by $\vec{X} \in C^1[0, T]$ the solution to

$$\vec{X}' = \vec{F}(c, \vec{X}), \ \ \vec{X}(0) = \vec{X}^0$$

Then $\vec{W}_n = \vec{X}_n - \vec{X}$ is solution to

$$\vec{W}_n' = \vec{F}(c_n, \vec{X}_n) - \vec{F}(c, \vec{X}), \ \ \vec{W}(0) = \vec{0}$$

Now observe that

$$\vec{F}(c_n, \vec{X}_n) - \vec{F}(c, \vec{X}) = \vec{F}(c_n, \vec{X}_n) - \vec{F}(c, \vec{X}_n) + \vec{F}(c, \vec{X}_n) - \vec{F}(c, \vec{X})$$

and by the smoothness of $\vec{F}$, the boundness of $\vec{X}_n$ and $\vec{X}$ and the linear dependence of $\vec{F}$ on c we have the following bounds

$$\|\vec{F}(c_n, \vec{X}_n) - \vec{F}(c, \vec{X}_n)\| \leq C\|c_n - c\|$$

and

$$\|\vec{F}(c, \vec{X}_n) - \vec{F}(c, \vec{X})\| \leq K\|\vec{W}_n\|$$

From these last two inequalities we get the differential inequality

$$\|\vec{W}_n'\| \leq K\|\vec{W}_n\| + C\|c_n - c\|, \ \ \vec{W}(0) = \vec{0}$$

which implies

$$\max_{[0,T]} \|\vec{W}_n\| \leq C \max_{[0,T]} |c_n - c| e^{KT}$$

Hence,

$$\max_{[0,T]} \|\vec{W}_n\| \to 0$$

as $n \to \infty$ i.e.

$$\max_{[0,T]} \|\vec{X}_n - \vec{X}\| \to 0$$

as $n \to \infty$. Finally, noting that

$$\mathcal{L}(c_n) = \int_0^T f(t, c_n, \vec{X}_n) dt$$

and since f is continuous in all variables $(aD' = \delta X_4)$, $\max_{[0,T]} \|\vec{X}_n - \vec{X}\| \to 0$ and $\max_{[0,T]} |c_n - c| \to 0$ we finally obtain

$$\mathcal{L}(c_n) \to \mathcal{L}(c)$$

as $n \to \infty$.

[8]Here $\|\vec{X}\| = \max_{1 \leq i \leq 6} \left\{ \max_{[0,T]} |X_i(t)| \right\}$

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Remark 5.2. *Clearly, existence of a minimum of the functional can be derived in the more general class of controls that are uniformly Lipschitz continuous in* $[0,T]$ *with values in* $[c_0,1]$ *again by compactness and continuity of* $\mathcal{L}$.

5.2. **The first order optimality conditions.** We now derive the first order optimality conditions in the form of Pontryagin minimum principle, [Pontryagin, 2018], for the constrained optimization problem

$$\min_{c\in\mathcal{K}} \mathcal{L}(c) = \min_{c\in\mathcal{K}} \int_0^T e^{-rt}\left[\frac{1-\left(c(t)^{\theta}\,[S+E+A+R]\right)^{1-\sigma}}{1-\sigma} + aD'(t)\right]dt \tag{14}$$

under the constraint

$$\vec{X}' = \vec{F}(c,\vec{X}),\ \ \vec{X}(0)=0. \tag{15}$$

where $\mathcal{K}$ is the class of controls defined in the previous section. Let $\vec{X}^*$ and $c^*\in\mathcal{K}$ be the optimal pair for the above constrained minimization problem.

Then the augmented Hamiltonian is

$$\mathcal{H} = e^{-rt}\left(\frac{1-\left(c^{\theta}\,[S+E+A+R]\right)^{1-\sigma}}{1-\sigma} + a\delta I + e^{rt}\vec{\lambda}\cdot\vec{F} + e^{rt}w_1(1-c) + e^{rt}w_2 c\right)$$

and considering now

$$\tilde{\mathcal{H}} = e^{rt}\mathcal{H} = \frac{1-\left(c^{\theta}\,[S+E+A+R]\right)^{1-\sigma}}{1-\sigma} + a\delta I + e^{rt}\vec{\lambda}\cdot\vec{F} + e^{rt}w_1(1-c) + e^{rt}w_2 c$$

where $\vec{\lambda} = (\lambda_S,\lambda_E,\lambda_A,\lambda_I,\lambda_R,\lambda_D)$, w_1 and w_2 are two non-negative functions. Set $\vec{\mu} = e^{rt}\vec{\lambda}$ and $v_1 = e^{rt}w_1$, $v_2 = e^{rt}w_2$, then we can express the optimality conditions in terms of the Hamiltonian $\tilde{\mathcal{H}}$, i.e.,

$$\tilde{\mathcal{H}}^*_c = 0$$

where $\tilde{\mathcal{H}}^*_c$ indicates the derivative with respect to c of $\tilde{\mathcal{H}}(c,\vec{X}^*,\vec{\mu}^*,v^*)$, i.e.

$$-\theta c^{\theta(1-\sigma)-1}(S^*+E^*+A^*+R^*)^{1-\sigma} - \mu^*_S\beta S^*(sI^*+E^*+A^*) + \mu^*_E\beta S^*(sI^*+E^*+A^*) - v^*_1 + v^*_2 = 0$$

where $v^*_1, v^*_2 \geq 0$ and the vector $\vec{X}^*$ and $\vec{\mu}^*$ are respectively the solution of the direct problem and of the adjoint linear problem along the optimal solution $c = c_*(t)$, that is

$$\begin{cases} \mu'_S - r\mu_S &= c_*^{(1-\sigma)\theta}(S^*+E^*+A^*+R^*)^{-\sigma} + \mu_S(n+\beta c_*(sI^*+E^*+A^*)) - \mu_E\beta c_*(sI^*+E^*+A^*) \\ \mu'_E - r\mu_E &= c_*^{(1-\sigma)\theta}(S^*+E^*+A^*+R^*)^{-\sigma} + \mu_S\beta c^* S^* - \mu_E(\beta c^* S^* - (\kappa+n)) - \mu_A(1-\epsilon)\kappa - \mu_I\kappa\epsilon \\ \mu'_A - r\mu_A &= c_*^{(1-\sigma)\theta}(S^*+E^*+A^*+R^*)^{-\sigma} + \mu_S\beta c_* S^* - \mu_E\beta c_* S^* + \mu_A(\gamma+n) - \mu_R\gamma \\ \mu'_I - r\mu_I &= -a\delta + \mu_S\beta s c_* S^* - \mu_E\beta s c_* S^* + \mu_I(\gamma+\delta+n) - \mu_R\gamma - \mu_D\delta \\ \mu'_R - r\mu_R &= c_*^{(1-\sigma)\theta}(S^*+E^*+A^*+R^*)^{-\sigma} + \mu_R n \\ \mu'_D - r\mu_D &= \mu_S n - \mu_D\delta, \\ \vec{\mu}(T) &= 0 \end{cases}$$

One can use the optimality conditions to compute the optimal control in a larger class of functions and use it as benchmark for the suboptimal control that we find in the class $\mathcal{K}$.

5.3. **On uniqueness of the optimal control.** The functional $\mathcal{L}$ in (12) is in general not convex, and there are no reasons to expect uniqueness of the optimal control in $\mathcal{K}$. In fact, in some cases the cost functional appears to undergo a phase transition in the social cost of COVID-19 death a. Typically, real valued functions of systems undergoing a phase transition are convex in one phase and concave in the other (see, e.g., the percolation probability as function of its intensity parameter, [Gandolfi, 2013], Figure 2.3), which is a further justification for the observed loss of convexity of $\mathcal{L}$. In addition, at the critical value of a multiple optimal controls can appear.

In the simple case of a unique, long term lockdown imposed at Day 85 to an opening level $\bar{c}$, and by a suitable choice of the parameters within the realistic ranges described below in Section 6.1, one can numerically find a value of a for which there are two minimizers of $\mathcal{L}$.

A graph of $\mathcal{L}$ is plotted in Figure 5.3 as function of $\bar{c}$. At the selected value of a, an optimal strategy is to exert no lockdown, but another optimal solution is to impose an opening level $\bar{c} = 84$. The two solutions have different overall mortality and GDP loss, but the same value of the loss functional, hence they are equivalent for the social planner, and for all those agreeing with her/his parameter selection and perceived social cost of a COVID-19 death.

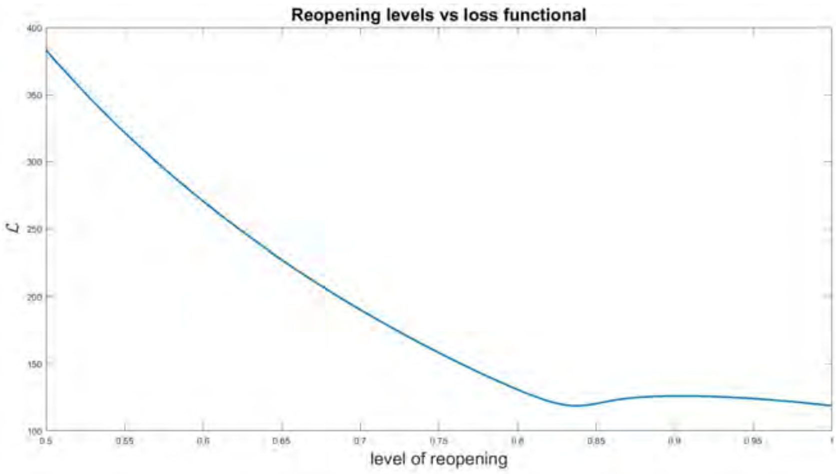

FIGURE 3. An example of two minima. $\mathcal{L}$ as function of the reopening intensity $\bar{c}$ applied from day 85 to 460. The social cost of Covid death is fixed at $a \approx 7833,11$ and $r = 0.00001$. See Section 6.1 for the other parameters.

At values of a which seem to better reflect current valuations, that is for a higher value of the social cost of Covid deaths, see Section 6.1, the minimum is likely to occur in the phase in which $D(t)$ is also convex, which is at lower values of $\bar{c}$, and therefore it is unique. This is the case in all the examples of the next section.

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6. Examples of optimal policies.

6.1. **Parameter selection.** There is a large variability in the estimations of the COVID-19 infection rate β [Toda, 2020]; we adopt the average value of $\beta \approx 0.25$. The reduced exposure to infected individuals who have developed symptoms is difficult to estimate: we start from a factor of $s = 0.1$ and carry out a sensitivity analysis. Duration of the latency period after infection and before symptoms are developed has been estimated in about 5 days (see for example [Li et al., 2020] and [Kai-Wang et al., 2020]), so that $\kappa \approx 0.2$. The fraction of asymptomatic is also quite problematic, with estimates ranging from 5% to 60%; we take an average value of $(1-\epsilon) = 1/3$, estimated in one of the studies, [Nishiura et al., 2020]. Similarly, the average recovery period is about 7 days, for mild cases [Byrne et al., 2020], suggesting $\gamma \approx 0.14$ for the recovery rate of an asymptomatic; in general, more severe cases worsen after about 7 days, requiring hospitalization, which completely excludes them from the possibility of transmission: for this reason, we also use the same value of $\gamma \approx 0.14$ for moving these cases from the infected to recovered, where most of them eventually will be; one fraction eventually dies, with the rate discussed now. The death to recovery rate is a highly controversial value, as both the recorded number of infected and deaths are affected by error which could range to 1000%. We take $\delta/\gamma \approx 0.02$ in such a way that the overall mortality rate in the population if the epidemics spreads without control ends up being about 1%; this is in line with several studies and observations: [Basu, 2020] estimates a US mortality of 1.3%; the Institute Pasteur indicates 0.53% [Salje et al., 2020]; and several locations have observed an increase of overall mortality up to six-fold [ISTAT, 2020]; this is compatible with a COVID-19 death rate of about 1% spread over the two months very likely needed for the uncontrolled virus to infect everyone in a limited area. Finally, the natural mortality rate is taken to be 3×10^{-5} corresponding to about 12 death per year per 1000, which is an average natural mortality rate in industrialized countries.[9]

With these assumptions, the equations become

$$\frac{dS}{dt} = -0.25\ S\ c(t)(0.1\ I + E + A) - 0.00003S + 0.00003(1 - D) \tag{16}$$

$$\frac{dE}{dt} = 0.25S(0.1I + E + A) - (0.2 + 0.00003)E \tag{17}$$

$$\frac{dA}{dt} = 0.2/3E - (0.14 + 0.00003)A \tag{18}$$

$$\frac{dI}{dt} = 0.4/3E - (0.14 + 0.00283)I \tag{19}$$

$$\frac{dR}{dt} = 0.14(A + I) - 0.00003R \tag{20}$$

$$\frac{dD}{dt} = 0.0028I \tag{21}$$

$$\frac{dD_N}{dt} = 0.00003(S + E + A + I + R) \tag{22}$$

As we take as initial time a very early stage of the epidemic outbreak (for all countries except China), we assume that the number of initial exposed is very small, in the order of one in a million; hence we take $S(0) = 1 - 10^{-6}, E(0) = 10^{-6}, A(0) = I(0) = R(0) = D(0) = 0$. A more accurate model, taking care of the geographical dispersion of the population would include different contact rates for individual living in far away areas [Gatto et al., 2020].

As a verification of parameter selection, we show that the mortality reproduces current observations, see Figure 4. Figure 5 illustrates the risk of a restart of the outbreak after the first reopening.

[9] https://data.worldbank.org/indicator/SP.DYN.CDRT.IN

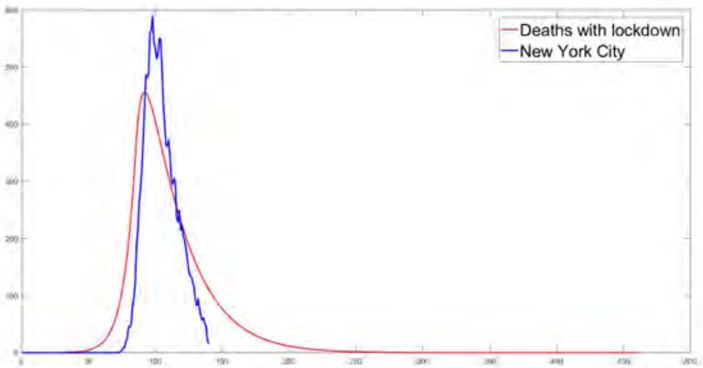

FIGURE 4. Covid deaths for an outbreak followed by lockdown at Day 85. Comparison is with real data of NYC. Notice that NYC seems to have a slightly higher transmission rate β, and has imposed a stricter containment policy than the one assumed by the graph of the mortality in our model. Note: the model is calibrated to fit cities or equivalent homogeneous areas and does not represent an entire country.

The yearly discount rate r in various developed countries is currently in the range -0.75 to 5.5%; we assume a discount rate of 4% but we check the impact of a wide range of alternative assumptions in the sensitivity analysis. The exponent σ of the function $\mathcal{V}$ is taken to be $\sigma = 2$, leading to an intertemporal elasticity of substitution within the year of $1/2$.

The elasticity parameter θ needs to be considered carefully. To estimate it, we recall that the reproduction number (8) has been estimated in various countries before and after a lockdown, see Table 1. From (9), at each point in time

$$\log P = \theta (\log c(t)) + \log(S + E + A + R)$$

so that, considering two times, t^- shortly before, and t^+ shortly after a lockdown, we have

$$\log \frac{P(t^+)}{P(t^-)} \approx \theta \left(\log \frac{c(t^+)}{c(t^-)} \right) \approx \theta \log \frac{\mathcal{R}(t^+)}{\mathcal{R}(t^-)},$$

where in the first approximation, we neglected the variation in the potential labor force $S+E+A+R$, sinc,e between t^- and t^+, the labor force available for production is assumed to be only impacted by the variations in c; the second approximation follows from (8) again neglecting variations in $S(t)$ in the short interval. This gives the estimate

$$\theta \approx \log \frac{P(t^+)}{P(t^-)} / \log \frac{\mathcal{R}(t^+)}{\mathcal{R}(t^-)}. \quad (23)$$

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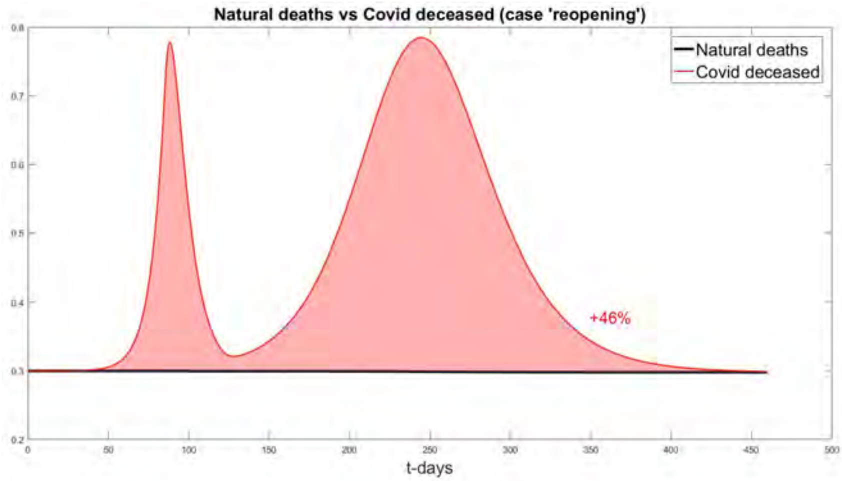

FIGURE 5. Total deaths for an outbreak, followed by lockdown at Day 85, and reopening at Day 120. The percentage represents the increase of deaths with respect to the natural ones. Note: the model is calibrated to fit cities or equivalent homogeneous areas and does not represent an entire country.

Table 1 shows various examples of co-variations of $\mathcal{R}$ and instantaneous GDP variations estimating from now-casting studies from various economic and statistical institutions after the lockdown from various countries. The parameters displayed have different sources. Some come from estimates based on data, other are simulated from epidemiologic models, and some are used in calibrations in economic papers, as a way to compare ourselves to the previous studies. The variability in the value of θ in the table is due to this diversity of methods. The range is between 0.166 and 1.142, with an average of 0.27 and a s.d. of 0.12. We select a value of 1/3 that can be adapted to any country or period as indicated in the table.[10]

In order to identify the time horizon of our analysis, we make several assumptions about the evolution of the epidemic. In particular, we assume that the policy assessment can be made with a specific time frame in mind, after which technological advancements like a therapy or a vaccine will drastically reduce the negative effects of the infection: [HHS, 2020] and [Le et al., 2020] predict a vaccine in early 2021, and challenge trials will anticipate things even further. We then assume a prototypical situation in which the epidemic has started unobserved in January 2020, and we assume that it will resolve at the end of the first quarter of 2021, hence we take $T = 460$ days. Clearly, these periods are only indicative, and one can adapt the time frame when more reliable perspectives are identifiable.

[10]A careful reader might notice that in the last row, the variation of the reproduction number and our best GDP response correspond to a value of $\theta = 0.290$, slightly below our parameter choice (1/3), the difference being due to the approximation in Equation 23.

Table 1. Alternative values of θ, from various studies and variants.

Country/Region	GDP loss (Instantan. or monthly)	$\log \frac{P(t^+)}{P(t^-)}$	Source	$\mathcal{R}(t)$	$\log \frac{\mathcal{R}(t^+)}{\mathcal{R}(t^-)}$	Source	**Implied θ**
France	-36%	-0.405	(A)	From 3 to 1	-1.099	(0)	**0.369**
France (2)	-	-	-	From 3 to 0.5	-1.792	(b)	**0.226**
France (3)	-	-	-	From 3.15 to 0.27	-2.457	(a)	**0.165**
Italy	-36%	-0.405	(B)	From 3.54 to 0.19	-2.925	(a)	**0.139**
Germany	-30%	-0.357	(B)	From 3 to 1	-1.099	(c)	**0.325**
Germany (2)				From 3.34 to 0.52	-1.860	(a)	**0.192**
Sweden	-20%	-0.223	(B)	From 3.04 to 2.02	-0.409	(a)	**0.545**
US (late March)	-10.0%	-0.105	(C)	From 1.50 (to 1)	-0.405	(d)	**0.260**
US (2) (late March)	-	-	-	From 2,20 (to 1)	-0.788	(e)	**0.134**
US (3) (late March)	-10%	-	-	From 2 to 1	-0.693	(f)	**0.152**
US (4) (May)	-31.0%	-0.371	(C)	From 3 to 1	-1.099	(0)	**0.338**
US (5) (May)	-34.9%	-0.430	(D)	From 3 to 1	-1.099	(0)	**0.391**
Our preferred benchmark	-23.3%	-0.265	-	From 2 to 0.8	-0.916	(*)	**1/3**

Notes: specification and sources.
(0): Priors; (*): our simulated benchmark outcome; (a): [Bryant and Elofsson, 2020]; (b): [Dimdore-Miles and Miles, 2020]
(c): [Hamouda et al., 2020]; (d): [Eichenbaum et al., 2020] ; (e): [Riou and Althaus, 2020]
(f): [Jones et al., 2020]; (A) INSEE, April 2020, Point conjoncture
(B) OECD Nowcasts, Coronavirus: The world economy in freefall, http://www.oecd.org/economy/
(C) Fed Atlanta GDPNow tracker (8/10/2020)
(D) New York Fed Staff Nowcast https://www.forexlive.com/centralbank/!/the-ny-fed-nowcast-tracks-2q-growth-at-3122-20200508
(E) Sweden: Forecast for 2020 are estimated to be between -6.9% and 9.7% by Statistics Sweden and the Riskbank, approx. 2/3rd of the decline in France.
https://www.cnbc.com/2020/04/30/coronavirus-sweden-economy-to-contract-as-severely-as-the-rest-of-europe.html

The choice of the social cost a of a Covid death is particularly complex, as it depends on a variety of socio-political and economic factors. We take a value of $a \approx 10,000$. To assess a value of a, note that it implies from Table 7 a decline of GDP of 76.7% from day 85 to day 460, that is a loss of yearly GDP equal to $\frac{460-85}{365} \times 0.767 = 0.7886$, that is, a 21.2% decline in yearly GDP. The gain is a decline in mortality of 0.74%. If these numbers where applied to the case of France, with a GDP of 2778 billions USD in 2018 and a population of 67 million, each live saved would correspond to 1.758 million USD. This is smaller than the statistical value of life currently estimated in developed economies, that is closer to 3 million euros [Baumstark et al., 2013] but one has to remember that most of the fatality have been for older individuals. According to various statistical sources [Statista, 2020], only 10% of the deaths were aged below 65, while 71% were aged above 75. We also report in Appendix Table 11 the fatality rates by age as available from recent studies. This implies that the right value for the statistical value of life in the exercise has to be lower than the usual estimates [Lee et al., 2009]. Another factor is that the government lockdown was based on lower estimations for the proportion of deaths. The current range is large, going from 0.4% for symptomatic according to the CDC or 0.37% per infected in the so-called Gemeinde Gangelt study in Germany [Streeck et al., 2020] to more than 4%.

Note that taking into account the risk aversion of the loss function does not change significantly the numbers involved and the order of magnitudes are preserved: risk-aversion mostly affect the numbers as $(0.9)^2$ that is by 20% only. To see this, consider a small time interval of length $\Delta t = 1$, so that the loss function is $(\mathcal{V}(P)\Delta t + aD)$ where D is the number deaths over that interval: differentiating the expression along the iso-loss curve, the slope of the iso-loss (indifference) curve is exactly:

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$$\frac{dP}{dD} = \frac{a}{-\mathcal{V}'(P)} = \frac{a}{P^{-\sigma}} = aP^{\sigma}$$

hence the adjustment factor is of the order of magnitude of the fraction of loss of GDP P to the square.

It is seen in the examples below that this value of the social cost of Covid death corresponds to prefer a substantial mortality reduction over GDP preservation, a phenomenon that, although sporadically opposed by some political groups, has found substantial support in most industrialized countries [Survey, 2020]. Such value of a is large enough that the optimal control functions determine an effective containment of the spread of the virus; this implies that the minimum of $\mathcal{L}$ occurs where the total mortality is also likely to be convex as function of the control, and that the minimum is likely to be unique (see Section 5.3).

We analyze below several examples of containment:

- A first policy is a containment with opening level $\bar{c}$ until the end of the study period.
- A second policy is a containment with opening level $\underline{c}$ till day 120, followed by a higher opening level $\bar{c}$ until the end of the study period.
- A third policy is to implement several cycles of alternated higher and lower opening .

As the presence of the virus went substantially unnoticed in the early stages in most locations, and then some time we needed to pass the required legislation, we assume that all lockdowns begin on day 85; this corresponds to March 25. Lock down in most countries, except China, started between March 9 and April 23, with a median on March 25[11]. When considering reopening, we use Day 120, which corresponds to April 29. For countries which have substantially reduced containment measures as of May 5th, the median end date of lockdown has been April 24, with about 20 countries still in lockdown.

All the numerical examples below are computed by Matlab R2016, using discretized ordinary differential equations ("ode45" or "ode23tb" functions) and integrals.

6.2. **Optimal unique lockdown.** We consider in this section a unique lockdown measure imposed on Day 85 (March 25): the opening level is reduced at level $\bar{c}$, and these restrictions are kept in place for the entire period, which is till Day 460, April 4, 2021. While this could have been a viable policy, implementing a moderate containment, the extent of the resulting GDP loss turns out to be dramatic. Figure 1 compares production reduction and mortality for the various levels of $\bar{c}$.

The optimal opening level is numerically determined to be $\bar{c} = 76.7\%$. Figure 6 compares the optimal containment policy with the case of no containment; Figure 7, compares the optimal case with two different policies corresponding to less or more reduced opening levels.

Table 2. Single extended lockdown.

	Epidemic No policy	Insufficient restrictions Fig. 7.B	Optimal Fig. 7.A %	Excessive restrictions Fig. 7.C
Containment and opening level $\bar{c}$	100%	87.4%	76.6%	46.6%
Mortality at Day 85	0.03%	0.03%	0.03%	0.03%
Total mortality at Day 460	1.03%	0.63%	0.26%	0.11%
Total mortality reduction	0%	38.47%	74.85%	88.96%
Annualized 1st quarter GDP loss	2.42%	2.89%	3.29%	4.43%
Total annualized GDP loss	1.78%	11.28%	19.45%	43.67%
Value loss functional	129.53	88.45	75.82	130.59

[11] https://en.wikipedia.org/wiki/National_responses_to_the_COVID-19_pandemic

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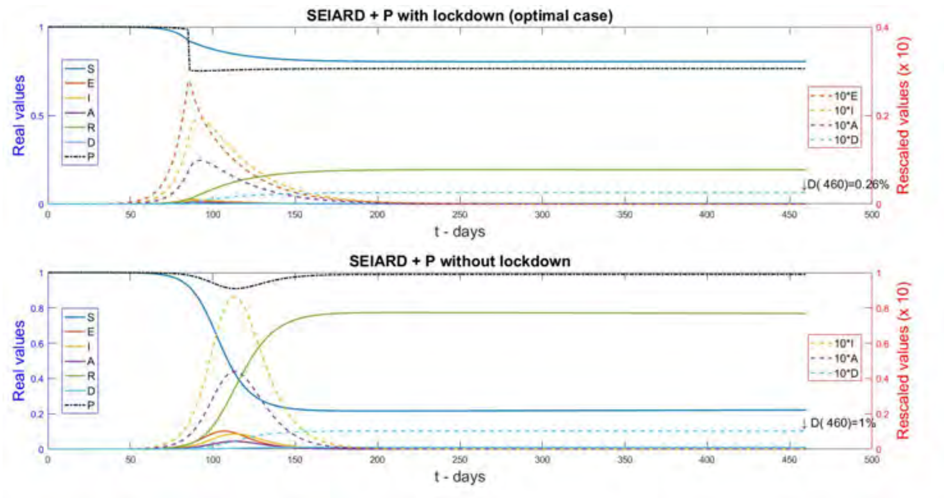

FIGURE 6. Comparison between the optimal moblity level and the case of no restrictions.

Notice that in case of no restrictions, the total mortality is about 1%, and annualized GDP loss due to passage of the virus is 1.78%. As noted in the Introduction, the lockdown realizes a sharp containment of mortality, but the constraint of protracted measures causes a dramatic GDP loss.

Figure 8 compares the time evolution of the reproduction numbers in the cases of optimal lockdown and no lockdown: notice that the optimal lockdown quickly brings the reproduction number to slightly below 1, keeping it there for the entire period.

6.3. **Optimal reopening level.** Most countries have imposed severe restrictions after a first period, which is at Day 85 in our model, followed by a sizeable reopening after about two months. To simulate this situation, we assume that at Day 85 the opening level has been fixed at $\underline{c} = 0.5$; as the previous example shows, this would not be optimal if imposed for a long time, and it incorporates the assumption of a release after a relative short period. In accordance to the current reopening in many countries, the containment is relaxed to level $\bar{c}$ at Day 120. Clearly, in this case a loss of production has already been incurred because of the initial containment, and we have selected an opening level that reproduces the observed loss of GDP in the first quarter at an annual rate of 4-5%, see Table 3, Line 5.

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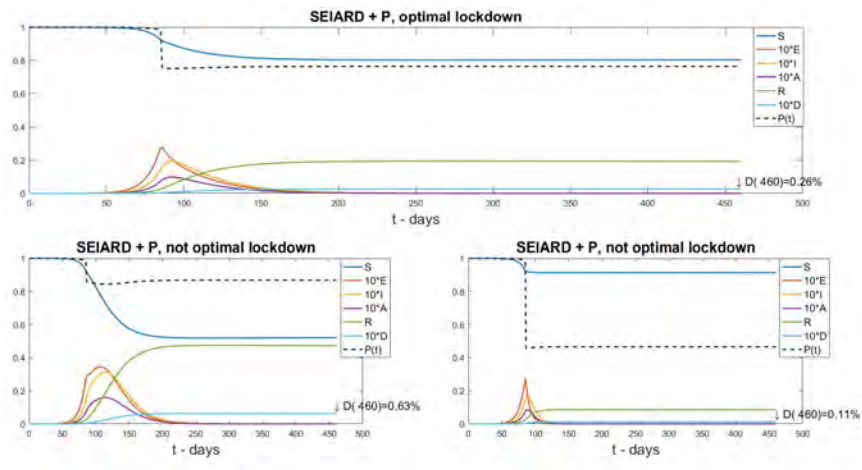

FIGURE 7. Fig. 7.A Top: optimal opening level and related epidemic variables. Fig. 7.B, Bottom left: a opening level higher than optimal. Fig. 7.C, Bottom right: a opening level below optimal.

We then numerically determine the optimal level of reopening, which turns out to be at $\bar{c} \approx 90.1\%$. Figure 9 compares the optimal solution with non-optimal ones, and a detailed comparison of some of the outcomes is carried out in Table 3.

TABLE 3. One reopening after a lockdown.

	Epidemic No policy	High reopening Fig. 9.B	Opt. reopening Fig. 9.A	Limited reopening Fig. 9.C
Reopening level $\bar{c}$	100%	96.8%	90.1%	66%
Mortality at Day 85	0.03%	0.03%	0.03%	0.03%
Total mortality at Day 460	1.03%	0.90%	0.63%	0.12%
Mortality reduction	0%	12.78	38.43	88.54
Annualized 1st quarter GDP loss	2.42%	4.30%	4.30%	4.30%
Total annualized GDP loss	1.78%	7.53%	12.02%	28.72%
Value loss functional	129.53	103.49	102.17	109.5

Notice that the optimal reopening level achieves a substantial herd immunity by the so called "flattening the curve". Because of that, the mortality reduction reaches 38.43% only, with a more moderate, but still sizeable, annualized GDP loss of 12.02%. Observe that deviations from optimality are extremely ineffective.

The reproduction number in Figure 10, after drastically decreasing and then going back higher, finally stabilizes around 0.8.

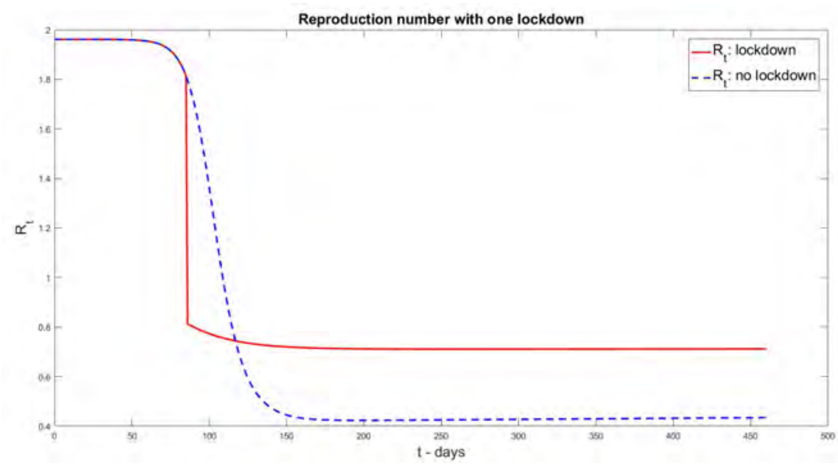

FIGURE 8. Reproduction number in the case of the optimal unique extended lockdown and without lockdown.

6.4. **Optimal periodic containment.** In this section we show some numerical results related to a periodic containment. We assume that after a drastic lockdown at an opening level of $\underline{c} = 0.5$, there is a complete reopening, followed by two more lockdowns at an opening level $\overline{c}$: we optimize over $\overline{c}$, see Figure 12. Production loss vs. mortality is plotted in Figure 11; notice the peculiar effect of too sharp lockdowns when these are reapplied at Days 170 and 230: because of excessive containment, the outbreak restarts later and the mortality ends up being higher even with more GDP loss than with the optimal control. A third lockdown would be necessary in this case.

The optimal opening level turns out to be $\overline{c} = 72.9\%$. This solution provides a moderate reduction in mortality with a contained economic damage at an annualized GDP loss of 7.44%, see Table 4. Herd immunity is reached with a very low number of infected at the time, which is shown in Figure 13 to be approximately Day 250, when the reproduction number is finally set to just below 1. This is the ideal strategy to achieve herd immunity, as discussed in [Moll, 2020], and it has been automatically identified by the optimization process.

6.5. **Optimization over three parameters.** In this example we optimize over three parameters: after a first, fixed containment from Day 85 to Day 120 at opening level $\underline{c} = 0.5$, two more containment periods take place, at opening level $\overline{c}_1$, each for a time length $\overline{\tau}$, interspersed with reopening at level $\overline{c}_2$: we optimize over $\overline{c}_1, \overline{c}_2$, and $\overline{\tau}$. A comparison of the optimal solution with others is in Figure 14; a summary is in Table 5; and the reproduction number is plotted in 15.

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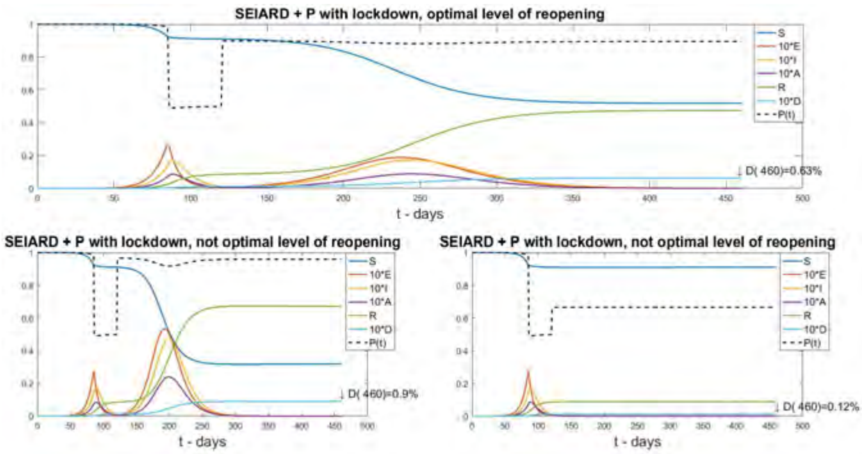

Figure 9. Fig. 9.A, Top: optimal reopening level. Fig. 9.B, Bottom left: an excessive reopening. Fig. 9.C, Bottom right: a suboptimal reopening level.

Table 4. Periodic containment optimized over the opening level during the two containments that follow a first, fixed one

	Epidemic No policy	Low lockdown Fig. 12.B	Opt. lockdown Fig. 12.A	Stricter lockdown Fig. 12.C
Second and third reopening level $\bar{c}$	100%	83.3%	72.9%	53.2%
Mortality at Day 85	0.03%	0.03%	0.03%	0.03%
Total mortality at Day 460	1.03%	0.84%	0.77%	0.78%
Mortality reduction	0%	18.13%	25.15%	24.36%
Annualized 1st quarter GDP loss	2.44%	4.32%	4.32%	4.32%
Total annualized GDP loss	1.78%	6.62%	7.44%	9.17%
Value loss functional	129.53	107.61	107.41	108.05

7. Sensitivity Analysis

We provide, in this section, a Sensitivity Analysis (SA) to evaluate how some of the parameters influence the minimum of the loss functional. Initially, SA is performed by a *global sensitivity analysis* approach using the Sensitivity Analysis tool of Matlab. Then, we also provide a local sensitivity analysis where we calculate the optimal policy varying one parameter at a time.

The global sensitivity approach uses a representative set of samples of parameters to evaluate the loss functional, which includes also the level of lockdown or reopening depending on the numerical experiment under investigation (see previous sections 6.2, 6.3 and 6.5). The workflow is as follows:

(1) For each parameter, including the opening level $\bar{c}$ during containment or reopening, we generate multiple values that the parameters can assume, namely we define the parameter sample

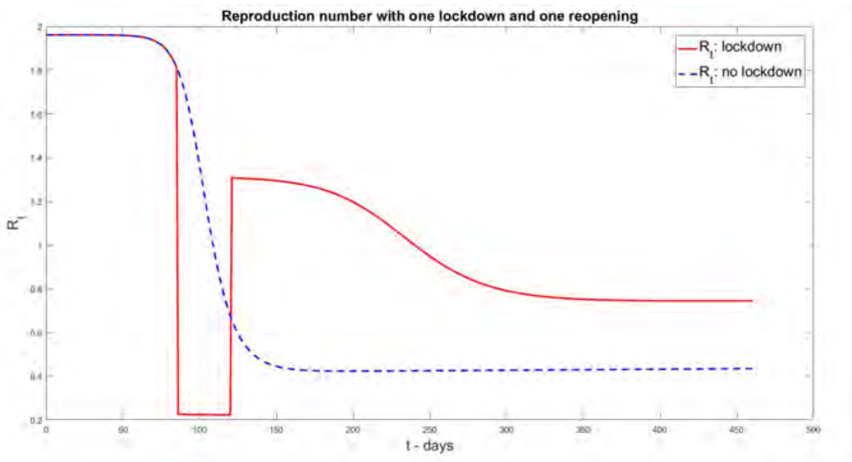

FIGURE 10. Reproduction number in the case of the optimal reopening.

TABLE 5. Periodic containment: optimization over opening level at containments, duration of containment, level of reopening.

	Epidemy No policy	Stricter policy Fig. 14.B	Optimal policy Fig. 14.A	Mild policy Fig. 14.C
Successive opening levels c	100%	80%	81.4%	85%
Level of reopening	100%	85%	91.8%	93%
Optimal period of closure (in days)	/	25	25	25
Mortality at Day 85	0.03%	0.03%	0.03%	0.03%
Total mortality at Day 460	1.03%	0.97%	0.84%	0.78%
Mortality reduction	0%	5.76%	17.85%	24.27%
Annualized 1st quarter GDP loss	2.42%	4.30%	4.30%	4.30%
Total annualized GDP loss	1.78%	10.63%	8.91%	8.18%
Value loss functional	129.53	102.89	102.6	102.14

interval by specifying a uniform probability distribution for each parameter. We create 200 combinations of these parameters.

(2) Then, find the solution of the SEAIRD model and evaluate the loss functional at each combination of parameter values and choose the combination which gives the minimum value of the loss functional.

(3) Fixing the "best outcome" combination found in (2), except the opening levels $\bar{c}$, we run again the optimization procedure, used in the previous sections, to find the optimal value of the opening levels for that combination of parameters.

Table 6 indicates the ranges for each parameter. As expected, the parameter that carries a greater weight on the functional value is represented by r. In fact, this is clear in Figure 16, where, as a

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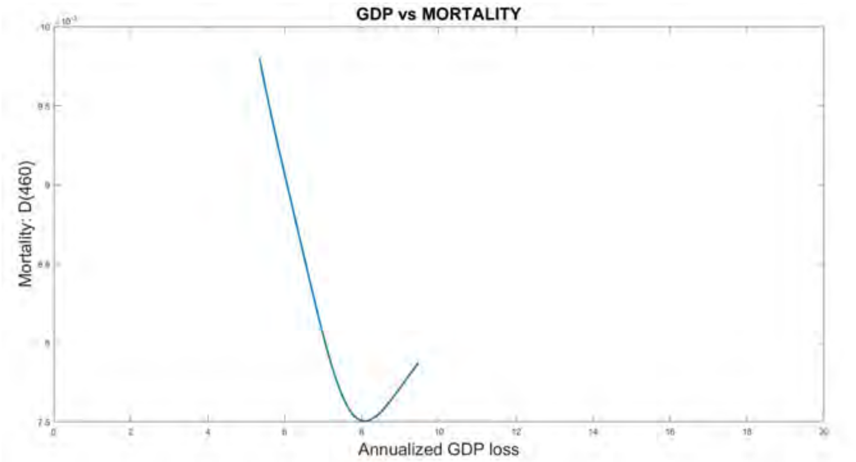

FIGURE 11. Production loss and fraction of deaths in a periodic containment; curve is parametrized by the opening level during the two containments that follow a first, fixed one.

TABLE 6. Ranges utilized for the sensitivity analysis

Parameter	Range
δ	$[0.0014, 0.0028]$
s	$[0.05, 0.15]$
r	$[0, 0.05]$
σ	$[1.01, 4]$
θ	$[\frac{10}{35}, \frac{1}{2}]$
a	$[8000, 20000]$
$\bar{c}$	$[0.5, 1]$

result of the sensitivity analysis, a tornado plot is displayed. The coefficients are plotted in order of influence of parameters on the loss functional, starting with those with greatest magnitude of influence from the top of the chart.

Below, for each numerical experiment, we provide a table comparing results from the optimal case determined with our methods, and the optimal case after the SA described in (2) and (3) above. For completeness, we also provide a local sensitivity analysis which is a technique to analyze the effect of one parameter on the cost function, and especially on the optimal policy. We take into account, as prototype, the first experiment where the optimal level of lockdown has to be found. See Table 10.

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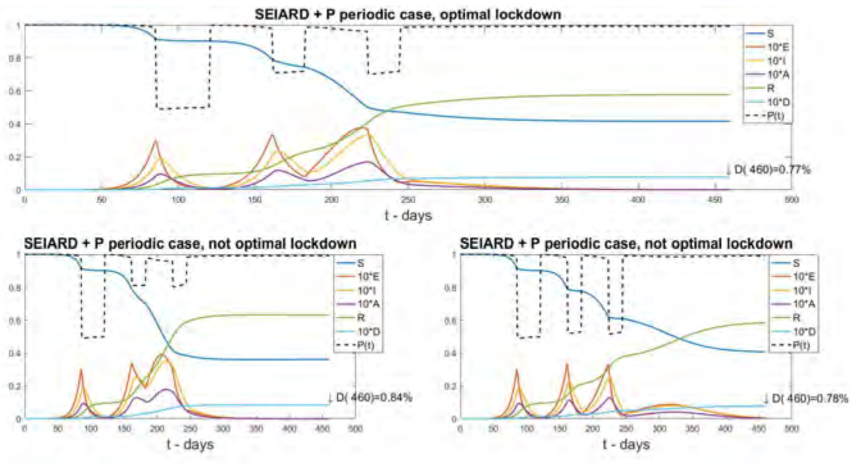

Figure 12. Fig. 12.A Top: optimal opening level. Fig. 12.B Bottom left: excessive opening. Fig. 12. C Bottom right: excessively reduced opening.

Table 7. Comparison of the optimal values of Section 6.2 with the result of the global sensitivity analysis

	Optimal case - Section 6.2	Optimal case - SA
Containment and reopening level $\bar{c}$	76.7%	75.3%
Mortality at Day 85	0.03%	0.02%
Total mortality at Day 460	0.26%	0.21%
Mortality reduction	74.85%	74.71%
Annualized 1st quarter GDP loss	3.29%	3.30 %
Total annualized GDP loss	19.45%	20.55%
Value loss functional	75.82	29.61

Table 8. Comparison of the optimal situation of Section 6.3 and of sensitivity analysis

	Optimal case - Section 6.3	Optimal case - SA
Reopening level $\bar{c}$	90.1%	93.9%
Mortality at Day 85	0.03%	0.03%
Total mortality at Day 460	0.63%	0.64%
Mortality reduction	38.43%	22.02%
Annualized 1st quarter GDP loss	4.30%	4.31%
Total annualized GDP loss	12.02%	9.41%
Value loss functional	102.17	33.47

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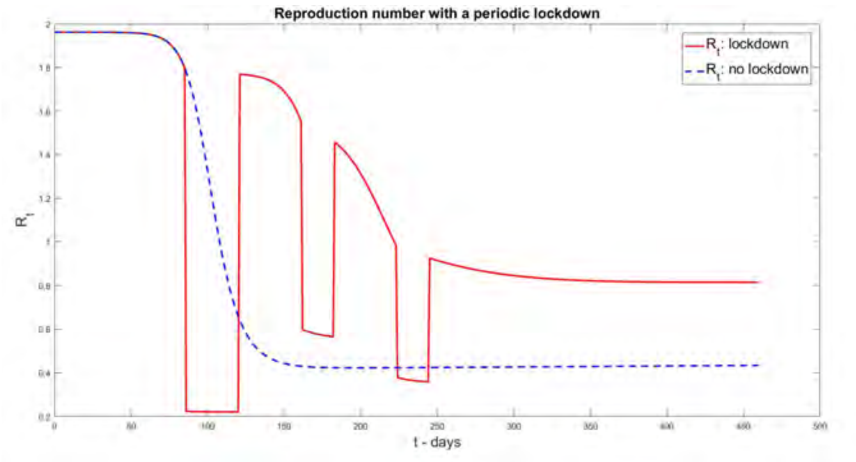

FIGURE 13. Reproduction number when control is optimized over the opening level during the two containments that follow a first, fixed one.

TABLE 9. Comparison of the optimal situation of Section 6.5 and of sensitivity analysis

	Optimal case - Section 6.5	Optimal case - SA
Successive reopening levels $\bar{c}$	72.9%	70.4%
Mortality at Day 85	0.03%	0.02%
Total mortality at Day 460	0.77%	0.63%
Mortality reduction	25.15%	24.98%
Annualized 1st quarter GDP loss	4.32%	4.28%
Total annualized GDP loss	7.44%	7.58%
Value loss functional	107.41	39.56

8. CONCLUSIONS

In this paper, we have formalized the trade-offs involved in the decision making between preserving economic activity and reducing the speed of diffusion of the pandemic. Our premise is that individual agents, as well as governments, want to contain and, possibly, postpone the infection and therefore the risk of a greater number of potential deaths to a later stage ("flatten the curve") in the expectation of better treatments, or a weakening of the virus, or a vaccine; we assume that actions are planned over a relatively short time horizon, that we choose to be 460 days. Our second working assumption is that there is a strong link between the degree of diffusion of the epidemic and the intensity of the economic shock, with an elasticity that varies in time and across countries but seems to be in a range around 1/3. This elasticity is the result of all changes in behavior of agents, from the economic lockdown itself to the greater precautions of consumers who reduce their consumption and firms who favor drastic reductions in working time. We have modeled

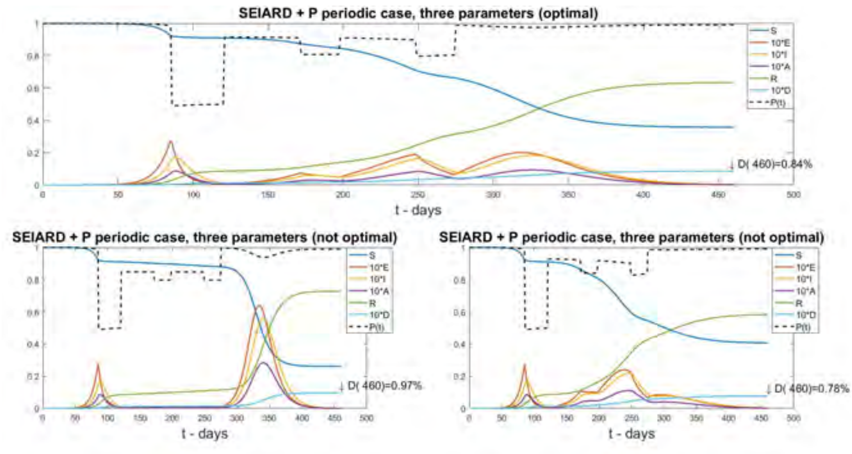

FIGURE 14. Fig. 14.A Top: Optimal policy in the case of three parameters: opening level at containments after the first, fixed one, duration of containments, and level of in-between reopening. Fig. 14.B Bottom left: a non optimal policy. Fig. 14. C Bottom right: excessive reopening.

TABLE 10. Local sensitivity analysis for optimal unique lockdown experiment.

Parameter	Range	Optimal opening level at containment at min range	at max range
δ	$[0.0014, 0.0028]$	81.4%	76.7%
s	$[0.05, 0.15]$	78.7%	75%
r	$[0, 0.05]$	100%	77.2%
σ	$[1.01, 4]$	74.4%	80.3%
θ	$[\frac{10}{35}, \frac{1}{2}]$	79.7%	72.6%
a	$[8000, 20000]$	78.4%	71.4%

containment measures by a function describing the level of opening, which we have taken to be piece-wise linear, with additional regularities, to include feasibility; we then formally described the trade-off between mortality reduction and limitation of economic loss which includes an estimation of the social cost a of COVID-19 mortality, and a discount rate which intensifies the effect of early deaths and early economic losses. We discussed the mathematical set-up and proved the existence of at least one optimal containment strategy. A parametric representation of mortality vs. economic losses illustrates the potentialities of the optimization approach.

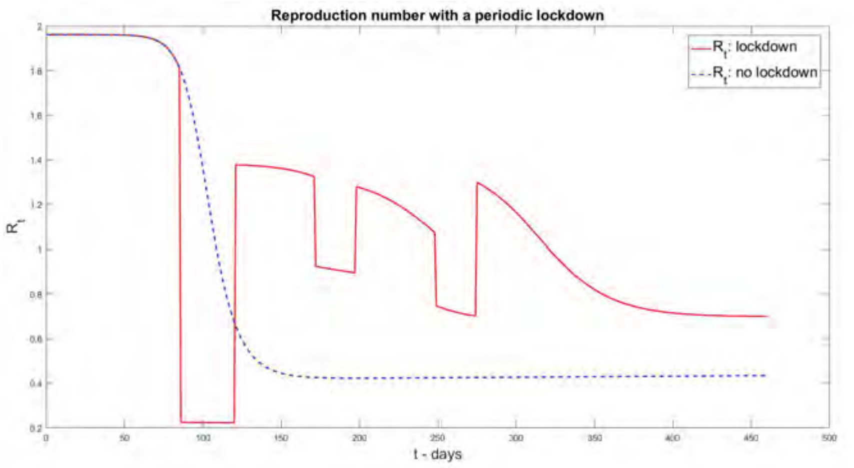

FIGURE 15. Reproduction number in the case of the optimization of three parameters.

Optimal control theory helps to find the right balance between the contrasting welfare needs during the COVID-19 epidemic, even when limited to few free parameters. It also sheds light on the possibility of a non uniqueness of the optimal control policy, very likely due to the non convexity of the loss functional. For instance, a transition of phases takes place in terms of the parameter a describing the social cost of COVID-19 mortality: at critical values of a, we observed the possibility of bifurcation towards two local optima and, therefore, discontinuous changes in the optimal policy as function of a. At and below the bifurcation, complete laissez-faire is optimal, but it is never preferred when the statistical value of a life is large enough.

Given that, for most countries, the implied value of the social cost of COVID-19 death a is in a range in which laissez-faire is not a viable solution, we discussed the optimal policies in a restricted set where the opening level can vary only a very limited number of times and where the solution turns out to be unique. Parameters have been estimated from available data, and a sensitivity analysis has been carried out on the main ones. We have analyzed various examples: one unique lockdown to be extended till the presumed end of the epidemic at the end of the first quarter 2021, a strategy that apparently very few countries tried to plan; a drastic, initial lockdown, followed by a reopening, which is what most countries are currently putting in place; some alternation of containment and reopening after the current one, which is a plausible outcome if the regained activity leads to recurrence of the virus. The results shed some light on the trade-offs involved, and suggests that gradual policies of longer duration but more moderate containment have large welfare benefits. On the other hand, after a sharp lockdown has been put in place, an alternation of containment and reopening is worth of consideration.

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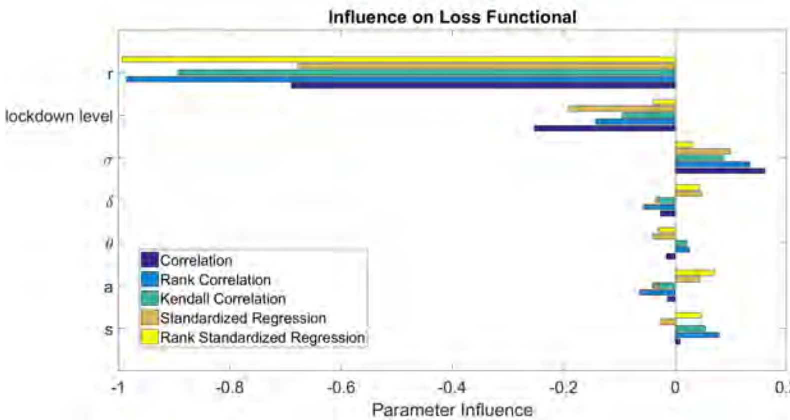

FIGURE 16. An example of the influence of the parameters on the loss functional for the first numerical experiment, with one unique lockdown.

Finally, we have investigated the sensitivity of the results on the estimated parameters. For most parameters, our results are insensitive to moderate errors in their selection. Among the significant ones, the most relevant has turned out to be the discount rate: this reflects the belief that early economic loss is more damaging, and that early deaths harm the health system and miss the opportunity of some form of adaptation to the virus or more effective treatments. In the examples we have considered a very high value for the discount rate, as we believe that treatment improvements are very likely. It follows that the timing is key to successful implementation of a containment policy, and that this is closely tied to the the pace and of the perspectives of potential technological advancement.

New York University in Abu Dhabi, May 28, 2020.[12]

[12]We wish to thank Christian Gollier and Benjamin Moll for comments on this draft.

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Appendix 1: A problem with capital and consumption with fixed saving rate (Solow type)

Social planner's objective. The social planner's utility $\mathcal{W}$ combines now consumption defined below. The social planner minimizes a loss function between an initial period $t = 0$ and final period T which could be infinity:

$$\mathcal{L} = \left\{ \int_0^T e^{-rt} \left[\mathcal{V}(C(t)) + aD'(t) \right] dt \right\}$$

Economy. Production combines labor, capital and the lockdown control strategy:

$$P = F[c(.), L, K]$$

where F is a Cobb-Douglas of each input with capital elasticity α. Note that here, the lockdown control only affects labor utilization, one could also put it outside the labor block but this is equivalent here.

Consumers save an exogenous fraction σ of output and use it to invest in capital. They also consume the rest, that is,

$$C(t) = (1 - \sigma)P(t)$$

NB: as in [Jones et al., 2020]*, it is possible to add a lockdown control* $c_c(t)$ *on the transformation of production into consumption: one forces agents to stop consuming and this reduces* β*.*

Capital stock is accumulated thanks to savings and depreciates at rate μ say 10% yearly and so follows:

$$\frac{dK}{dt} = -\mu K + \sigma F[c(t)L, K]$$

There is still a link between GDP and transmission, the lockdown policy is denoted by $c(t)$:

$$\beta_t = \bar{\beta} c(t)$$

Optimal control problem. The epidemic part is kept identical but adds one control $C(t)$ and one constraint:

$$\lambda_K \left[-\mu K + \sigma F[c(t)L, K] \right]$$

Appendix 2: A Ramsey first best problem

Now, let consumption be endogenous too, so that the saving rate is not constant.

The social planner's utility $\mathcal{L}$ combines now consumption defined below. The social planner minimizes the same loss function as before, between an initial period 0 and a final period T which could be infinity:

$$\mathcal{L}_{C(t),c(t)} = \left\{ \int_0^T e^{-rt} \left[\mathcal{V}(C(t)) + aD'(t) \right] dt \right\}$$

but now has two instruments: one is the lockdown control c(t), the second one is the consumption by agents $C(t)$, which determines at which rate the capital can be accumulated, namely:

$$\frac{dK}{dt} = -\mu K + F[c(t)L, K] - C(t)$$

Remark 8.1. *Existence of an optimal control can be shown similarly as for the case treated in the paper in both examples. In fact, in the first example the functional is clearly continuous in* c *since consumption* C *and capital* K *are continuous in* c *and consumption can be assumed, without loss of generality, to be bounded below by a positive constant* C_0*. In the second case we can prove existence of a minimizing pair* c^*, C^* *by compactness. In fact,* $c \in \mathcal{K}$ *and, by the properties of* c *and of the solutions of the SEIARD model, consumption* C *is a uniformly Lipschitz continuous. Also, we can assume that consumption takes values in a closed and bounded interval* $[C_0, C_1]$*. This allows us to minimize the functional over a compact subset of* $C[0,T] \times C[0,T]$ *where* $C[0,T]$ *indicates the space of continuous functions on the interval* $[0,T]$*. Finally, using the continuity of the functional with respect to* c, C *the existence of an optimal pair* c^*, C^* *follows.*

Remark 8.2. *In other problems, such as the Ramsey second best problem, the social planner may not be able to allocate consumption properly. Instead, private agents in a market economy choose themselves their consumption, maximizing their own utility function, leading to an arbitrage between consumption in different dates, corresponding to the traditional Euler equation in macroeconomics. This constraint is an additional constraint to the social planner and at this stage, our results do not apply to them.*

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Data Appendix

Table 11. Fatality rates by age.

	Fatality rates per age (in %)	
Age groups	China [Verity et al., 2020]	France [Salje et al., 2020]
0-9	0.00161	0.001
10-19	0.00695	(for 0-19)
20-29	0.0309	0.007
30-39	0.0844	0.02
40-49	0.161	0.05
50-59	0.595	0.2
60-69	1.93	0.8
70-79	4.28	2.2
80+	7.8	8.3
Less than 60	0.145	na
More than 60	3.28	na
Overall	0.657	0.53

Note: These figures refer to the ratio of probable deaths to infected population.

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Policies to support firms in a lockdown: A pecking order[1]

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We analyze government interventions to support firms facing liquidity needs during a lockdown in a competitive model of financial intermediation. Banks and firms have legacy balance sheets at the lockdown date. Firms' liquidity needs can be financed by banks that are subject to risk-weighted capital requirements and funded with insured deposits. An increase in firms' overall claims to external investors aggravates moral hazard problems and reduces expected output. The government can support firms directly through transfers or indirectly through guarantees to new bank loans or reductions in the capital requirement. As a result of the diversification of idiosyncratic firm risks conducted by banks, a reduction in the capital requirement only creates costs for the government following negative aggregate shocks that lead to banks' failure. A pecking order on the government policies that maximize output as a function of the government's budget is derived. For low budget, a reduction in capital requirements is optimal and is fully transmitted to firms through increases in banks' leverage. For medium budget, the capital requirement reduction becomes slack and needs be combined with transfers to firms or loan guarantees. For high budget, transfers are strictly necessary.

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1 The views expressed in this paper are our own and do not necessarily coincide with those of Banca d'Italia. We would like to thank Francesco Palazzo and Javier Suarez for helpful comments and discussions.

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1 Introduction

The economic lockdown measures necessary to contain the diffusion of the Covid-19 pandemics has created a liquidity problem for the corporate sector of an unprecedented magnitude in peace times. Authorities in most jurisdictions have rapidly responded by deploying a vast array of policies to support the entrepreneurial sector. These include direct transfers to cover part of their operating costs, guarantees on the new lending granted by banks, and a release of bank capital buffers to further loosen credit access conditions. While the ultimate objective of these measures is to ensure firms' survival to the liquidity crisis imposed by temporary lockdowns, little is known about their interaction, their implications for firms' and banks' riskiness and welfare in the medium term, and their overall cost for the taxpayer.

This paper provides a first theoretical contribution to the issue. We consider a government with limited fiscal capacity, and analyze welfare maximizing interventions during a lockdown that creates a cash-flow problem to the corporate sector due to a non-recoupable loss of revenues. Our framework exhibits firms' exposed to idiosyncratic and aggregate risks and a standard entrepreneurial moral hazard problem associated with external financing that is aggravated as firms' indebtedness increases due to the lockdown. A competitive banking sector that finances firms and diversifies their idiosyncratic risks is funded with insured deposits and subject to (risk-weighted) capital regulation. Capital requirements reduce the cost of deposit insurance but constraint banks' lending supply, creating intermediation rents that increase firms' financing cost and aggravate their moral hazard. The government can contain the amplification of the initial output losses implied by the lockdown by introducing policies that reduce the overall debt promise of firms to banks. We consider both direct measures in support of firms such as government transfers, and indirect measures that reduce their funding cost such as guarantees on new bank loans and reductions in capital requirements. We model the limited fiscal capacity of the government as some exogenous maximum expected cost it can afford when intervening.[1] The paper derives the following generic "pecking order" in the optimal intervention mix. First, for a government with a very low budget, intervening might be worse than not doing so, as it could lead to the inefficient continuation of highly indebted "zombie firms". Second, for a low budget government, it is optimal to rely exclusively on reductions on capital requirements, which are transmitted to firms by banks that increase leverage up to maximum and extend cheaper financing. The reason is that, due to the diversification of firms'

[1]The results would not change under the assumption that the government has a maximum expenditure capability under all possible contingencies and chooses interventions that satisfy such budget restriction in order to satisfy the following lexicographic objectives: i) maximize expected output in the economy; ii) minimize expected cost of the intervention.

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idiosyncratic risks done by banks, this policy creates costs to the government only following sufficiently negative aggregate shocks that lead banks to fail. Yet, as the government budget increases and banks' lending constraints get relaxed, competition reduces bank intermediation rents. There is a minimum capital requirement below which banks would not transmit a further loosening into cheaper financing to firms. That minimum capital requirement is attained for a government with a medium budget, at which point the capital requirement loosening needs be combined with loan guarantees or transfers to firms, which constitute perfect substitutes due to competition. For a high budget government, substitutability breaks down and direct transfers to firms are necessary.

We build a stylized competitive model of bank intermediation between depositors and firms that have productive projects exposed to both idiosyncratic and aggregate risks. Deposits are fully insured and the bank is subject to a minimum risk-weighted capital requirement regulation. We consider identical firms and banks with some existing balance sheets at the date in which an economic lockdown is introduced. The lockdown is modeled as an exogenous liquidity need experienced by firms that they must cover in order to continue their projects, as in Holmstrom and Tirole [1998]. We depart from that paper by assuming that firms do not have a pre-committed credit line and have to finance their liquidity needs from banks, which in turn need to raise new deposits. Yet, an increase in firms' debt aggravates the moral hazard problem implied by the non-observability of the entrepreneurs' effort, and leads to higher project risk and lower expected output.[2] The increase in project risk also creates losses for the banks in their existing portfolio of corporate lending, reducing the risk-weighted value of their legacy lending and limiting their capability to provide cheap new financing to the firms. This in turn further aggravates entrepreneurs' moral hazard, so that the model exhibits an amplification channel of expected output losses that operates through the balance sheet linkages between firms and banks. When the liquidity shock is large, firms are not able to obtain financing and are liquidated. When it is smaller, firms obtain financing but the expected payoff of their projects gets reduced due to the increase in indebtedness. Despite the increase in the risk of their outstanding loans, competitive banks' expected equilibrium profits augment because of the rents they obtain from the additional financing granted to firms due to the scarcity of lending capacity implied by the capital requirement regulation.

We consider a government that intervenes in order to contain the amplification of the initial output losses generated by the lockdown. The government has a maximum (expected) budget that can be used to deploy the three following policies. First, a direct transfer to firms. Second, a reduction in capital requirements, that relaxes banks' constraints to issue

[2] We assume a binomial pay-off structure for firms' projects so that the model does not distinguish between different forms of outside financing such as debt or outside equity. In this respect, the model set-up seems suitable for micro and small firms for which there is no separation between ownership and control.

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new deposits and supply liquidity to firms. Third, a guarantee on the new loans issued to the firms.[3] The entrepreneurial moral hazard implies that, conditional on firms' continuation, expected output in the economy is a strictly decreasing function of the firms' overall indebtedness. Support policies thus aim at minimizing the increase in firms' debt burden associated with satisfying liquidity needs during the lockdown. Direct transfers to firms do so by reducing the funds firms must raise from banks. Indirect policies in turn imply contingent government injections of funds that augment the banks' capability to issue deposits, and, due to competition, lead to cheaper bank financing of the residual liquidity needs.

The paper characterizes the optimal combination of these policies depending on the exogenous government's budget. Our results can be interpreted as providing a "pecking order" in the deployment of the support policies. First, interventions of a government with a very low budget might give rise to "zombie firms" and be worse than not intervening at all. When the liquidity shock faced by firms is high enough, in absence of a government intervention firms are not able to obtain the necessary financing from banks and are liquidated. By providing (direct or indirect) support to firms, the government can induce them to continue. Yet, as a result of the public intervention the overall value from continuation for the set of private stakeholders (firms, banks and the latter's debt investors) is higher than its social value, so that socially inefficient continuation might arise. That is the case when the intervention leads firms to exit the lockdown very highly indebted. Even though firms' continuation would be efficient at their pre-lockdown level of indebtedness, a government that cannot afford the cost of sufficient support would find optimal not to intervene at all and let firms be liquidated. The results show that the policy objective of ensuring firms' survival might be short-sighted and constitute a call for caution regarding the costs associated with keeping alive zombie firms through very low budget interventions.

Second, it is optimal to rely exclusively on a reduction of capital requirements provided banks respond by maximally increasing their leverage. We show that provided capital requirements are binding, the equilibrium firms' overall debt promise is decreasing in the overall amount of funds injected by the government at the initial and final dates conditional on the *ex-post worst* aggregate shock. Funds injected conditional on *ex-post good* aggregate shocks do not hence help in providing debt relief to the firms. These injections are in fact appropriated in equilibrium by the banks, and constitute a cost the government would like to avoid. This can be achieved by relying only on a reduction on capital requirements because by design this creates government disbursements only conditional on bad aggregate shocks in which banks fail and their size is just enough to ensure the banks' deposits are repaid in full. Transfers, which are uncontingent, and loan guarantees, which lead to

[3]The results in the paper are robust to allowing guarantees to cover also banks' legacy loans.

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some disbursements in good aggregate shocks due to idiosyncratic firms' risks, are thus suboptimal.

The optimality of using a loosening of capital requirements as only support policy depends on banks' finding optimal to respond by increasing leverage. We show that is the case for a government with a low budget, as it is only able to reduce capital requirements by a limited amount.[4] The intuition is that reductions on the capital requirement allow banks to increase leverage and expand their supply of new lending. As a result, banks' intermediation rents get eroded and firms obtain cheaper funding. The new lending increases the overall indebtedness of firms, which, due to the moral hazard, reduces the value of banks' outstanding loans. There is nevertheless a minimum equilibrium banks' capital ratio compatible with their optimal lending decisions. In fact, if banks were to operate with a sufficiently low capital ratio, that is with very large leverage, the equilibrium rents on new lending would become lower than the losses on outstanding loans, so that banks would prefer to liquidate the firms. This puts an upper limit on how much support the government can give to firms through loosening of capital requirements: Once the capital requirement achieves the minimum equilibrium market capital ratio compatible with banks' lending incentives, further loosening of capital requirements does not transmit to firms. A government with a medium budget can implement this minimum capital requirement and still have some spare budget to use in other policies. We show that due to competition across banks in the financing of firms' liquidity needs, transfers and loan guarantees are perfect substitutes in the optimal policy intervention mix in this government budget region. Interestingly, as the government budget increases and more transfers or loan guarantees are extended, the leverage chosen by banks gets reduced.

Our final result is that, when the government budget is large enough, then a strictly positive direct transfer to firms is a necessary measure in an optimal intervention. The intuition is that loan guarantees provide support to firms only to the extent that firms issue new debt, but the increase in overall debt promise to banks is the source of expected output destruction in this economy. When a government has a large budget it is thus optimal to directly target the increase in firms' indebtedness by making some direct transfers to the firms that reduce their financing need from banks.

The paper is organized as follows. Section 2 describes the related literature. Section 3 describes the benchmark set-up with no economic lockdown. Section 4 describes the model with a lockdown. Section 5 characterizes the optimal policy mix when intervention policies are restricted to transfers to firms and guarantees on banks' liabilities. Section 6 extends the analysis to allow also for loan guarantees in the intervention toolkit. Section 7 concludes.

[4]The government budget should not be very low, because in such a case no intervention would be preferable rather than inducing the suboptimal "zombie" continuation of firms described above.

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2 Related literature

From a modeling perspective, our paper is mostly related to Holmstrom and Tirole [1998]. That paper focuses on the ex-ante design of contracts for liquidity provision when firms anticipate the possibility of liquidity shocks and, due to moral hazard problems, face constraints on their ex-post external financing capacity. They highlight that, when all liquidity risk is idiosyncratic, a bank that grants credit lines to all firms achieves an efficient liquidity provision, while when all liquidity risk is aggregate, there is a role for the public provision of liquidity. Instead, in our analysis, the lockdown creates an aggregate unexpected liquidity shock, and we focus on ex-post liquidity provision given existing firms and banks' legacy debts. We assume that banks are funded with insured deposits and subject to a capital requirement that limits the cost of deposit insurance but constrains banks' supply of lending to firms, aggravating their moral hazard problem.[5] Our analysis of the interplay between firms' financing needs, banks' lending constraints and government interventions affects output is absent in Holmstrom and Tirole [1998]. Analogously to that paper, we also identify a key role for the presence of aggregate risk as it drives the optimality of intervening through a reduction in banks' capital requirements.

This paper is also related to theoretical contributions in which agency frictions give rise to external financing constraints for both banks and firms. Holmstrom and Tirole [1997], Repullo and Suarez [2000], Rampini and Viswanathan [2019], highlight how shocks to the net worth of one of the set of agents gets amplified due to balance sheet linkages, but do not consider optimal intervention design, which is the focus of our paper.[6] This issue is addressed in Villacorta [2020], which shows in a dynamic macroeconomic model that the optimality of bail-outs to firms or banks during crises depends on how negative shocks affect the sectorial distribution of net worth. The estimation of the model allows to identify the optimal bail-out target in recent recessions in the US. Our paper focuses on firms' liquidity problems associated with lockdowns and considers optimal policy design within a richer set of policy interventions.[7]

Our paper belongs to the growing literature that analyzes optimal interventions by fiscal

[5]Another difference from the set-up in Holmstrom and Tirole [1998] is that we consider a continuous moral hazard problem, so that output not only depends on whether firms are able to continue but also on their overall external claims upon continuation.

[6]In this respect, our paper is also related to Arping, Lóránth, and Morrison [2010], which analyze the optimality of supporting firms' investment through co-funding or loan guarantees in a set-up in which banks' net worth is not relevant.

[7]It is possible to prove that in our model transfers to banks, which could be interpreted as precautionary bank bail-outs, are always weakly dominated by transfers to firms.

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or monetary authorities during the Covid-19 crisis.[8] The initial contributions have focused on the role of fiscal and monetary policy interventions in macroeconomic models in which the lockdown gives rises to supply shocks that get amplified through demand factors (Guerrieri, Lorenzoni, Straub, and Werning [2020] and Caballero and Simsek [2020]), or creates falls in demand in some sectors which could potentially propagate to other sectors (Faria-e Castro [2020] and Bigio, Zhang, and Zilberman [2020]). Regarding the focus on support policies to firms, the closest paper to ours is Elenev, Landvoigt, and Van Nieuwerburgh [2020b], which builds on the banks and firms' balance sheet linkages dynamic macroeconomic framework developed in Elenev, Landvoigt, and Van Nieuwerburgh [2020a], and assesses quantitatively the effectiveness of different corporate relief programs introduced in the US. The paper finds that a combination of transfers to firms and fully insured corporate loans contingent on firms' idiosyncratic productivity is the most effective program as it enhances the allocation of credit in the economy. Our theoretical contribution instead stems from the optimality of using reductions in the capital requirements faced by banks funded with insured deposits. In fact, this provides aggregate risk insurance in the economy, and leads to corporate relief at the minimum cost for the government.

Finally, this paper is also related to the literature on optimal intervention design during financial or banking crises (see for example, Bruche and Llobet [2014], Philippon and Schnabl [2013], Segura and Suarez [2019]). In those papers, output losses result from asymmetric information or debt overhang problems that originate in the financial sector, and government interventions directly target this sector. In our paper instead the source of output losses stems from firms' moral hazard problems as their net worth gets reduced during a lockdown, and government interventions aim at mitigating those net worth losses. We show that for a government with low resources this is best achieved indirectly by allowing the banks that finance firms to increase their leverage and consequently the benefit from a larger subsidy on their insured deposit funding.

3 The benchmark model with no lockdown

We first describe the set-up, sequence of events and pay-offs in an economy in which there is no lockdown. This benchmark allows to understand the implications of a lockdown, which is analyzed from next section onwards.

Consider an economy with two dates, $t = 0, 1$, and four classes of agents: depositors, a

[8] A strand of papers has focused instead on the optimal health policy response given the interaction between the evolution of the pandemic and the macroeconomy (for example, Eichenbaum, Rebelo, and Trabandt [2020], Alvarez, Argente, and Lippi [2020], Acemoglu, Chernozhukov, Werning, and Whinston [2020], Jones, Philippon, and Venkateswaran [2020], Correia, Luck, and Verner [2020]).

measure one of entrepreneurs that own firms, a banker that owns a competitive bank that intermediates funds from depositors to firms, and a government that provides full insurance on bank's deposits and sets a minimum risk-weighted capital requirement regulation to the bank. All agents derive linear utility from consumption and have a zero discount rate. Both firms and the bank are run in the interest of their owners, and at the initial date have assets and liabilities in place resulting from some unmodeled prior decisions.

3.1 Firms

At $t = 0$, each firm has a project in place and some debt liabilities. In order to continue the project, the firm has to incur an operative cost ρ at $t = 0$. In absence of a lockdown, such cost is paid by the firm out of the revenue $r_0 \geq \rho$ that the project generates at $t = 0$. To fix our ideas, we assume that $r_0 = \rho$.

Conditional on incurring the operating cost, the project has a pay-off at $t = 1$ of $A > 0$ in case of success, and of zero in case of failure. The success or failure of a project at $t = 1$ depends on a firm-specific shock and an aggregate shock that are described below. The probability that the project succeeds is denoted with p and satisfies $p \in [0, p_{\max} < 1]$, where $p_{\max} < 1$. The success probability coincides with the unobservable effort intensity exerted by its entrepreneur between $t = 0$ and $t = 1$. We henceforth refer to the success probability p as the entrepreneur's effort, and also as the project's risk under the understanding that low values of p correspond to risky projects. An effort p entails the entrepreneur a disutility cost given by a function $c(p) \geq 0$ satisfying:

Assumption 1. *$c(0) = 0, c'(0) = 0, c'(p_{max}) \geq A, c''(p) > 0,$ and $c'''(p) \geq 0.$*

The first-best entrepreneur's effort, denoted with $\overline{p}$, maximizes expected project pay-off net of effort cost, expected output for short, and is given by:

$$\overline{p} = \arg\max_{p} \{pA - c(p)\}\,. \tag{1}$$

Assumption 1 implies that $\overline{p} \in (0, p_{\max}]$ and is determined by the first order condition:

$$c'(\overline{p}) = A. \tag{2}$$

Each firm has at $t = 0$ debt with notional value denoted b_0 that has to be repaid at $t = 1$. This debt is held by the bank that is described next.

Moral hazard in effort The unobservability of the effort choice creates a moral hazard problem. The firm chooses the project risk in order to maximize the residual claim of its

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owner. Since it will be useful later on, we consider a general debt promise $b \in [0, A]$ at $t = 1$. The firm's optimal risk choice, that we denote with $\hat{p}(b)$, is given by

$$\hat{p}(b) = \arg\max_{p} \{p(A - b) - c(p)\} \iff \quad (3)$$

$$c'(\hat{p}(b)) = A - b. \quad (4)$$

We have immediately from Assumption 1 the following result.

Lemma 1. *For given debt promise $b \in [0, A]$, the effort p chosen by the firm is a function $\widehat{p}(b)$ satisfying*

$$\frac{d\widehat{p}(b)}{db} < 0, \frac{d[\widehat{p}(b)A - c(\widehat{p}(b))]}{db} < 0, \hat{p}(0) = \bar{p}, \text{ and } \hat{p}(A) = 0.$$

Moreover, the expected value of the total debt promise $\widehat{p}(b)b$ is increasing in the interval $b \in [0, b_{max})$ and decreasing in $b \in [b_{max}, A]$.

The lemma states that as the total debt promise increases, the projects become riskier (p decreases) and their net pay-off falls. The reason is that when b is larger, the entrepreneur has less incentives to undertake the costly effort because the value created by this action is to a larger extent appropriated by the bank. Moreover, the lemma states that the expected value $\widehat{p}(b)b$ of debt with promise b is increasing in this variable only below a threshold $b_{\max}$. Beyond it, the moral hazard is so severe that additional increases in b reduce the expected value of the debt.

We assume that the original debt promise b_0 satisfies $b_0 < b_{\max}$, and we denote

$$p_0 \equiv \hat{p}(b_0) \quad (5)$$

the firm's risk choice under no lockdown.

Finally, a firm that does not incur the operating cost must liquidate its project and obtains a recovery value of R at $t = 0$. The firm then uses its available funds, amounting to $\rho + R$, to (partially) repay debt b_0 and the residual $(\rho + R - b_0)^+$ is distributed to the entrepreneur.

We assume that:

Assumption 2. $R < p_0 A - c(p_0) - \rho$.

The assumption implies that it is socially efficient to incur the operating cost and continue the project given the firm's debt and the risk choice it induces. We assume that the payment of the operating cost does not lead to rents to some unmodeled agents. Specifically, the operating cost is interpreted as the maintenance work at $t = 0$ necessary to

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preserve the productive capability of the project.[9]

It is immediate to check that Assumption 2 also implies that the entrepreneur finds optimal to continue the project.

Summing up, in absence of a lockdown firms use their $t = 0$ revenues to pay their operating costs, and continue their projects with risk p_0.

3.2 Bank

At $t = 0$, there is a representative bank that is the only agent with the capability to enforce debt repayment by firms. The bank holds the portfolio of firms' debt with promise b_0 and risk p_0 described above. The bank has deposits with a notional promise d_0 that are due at $t = 1$. Since the bank holds debt from all the firms in the economy, its asset portfolio diversifies idiosyncratic firms' risk and is only exposed to **aggregate risk**.

Specifically, at $t = 1$, an aggregate shock θ that affects the pay-off of all firms' projects is realized. Conditional on the realization of θ, the success probability of a project with risk choice p is θp. Hence, when $\theta > 1$ ($\theta < 1$) the conditional probability of a success is larger (lower) than its unconditional value. In addition, conditional on θ, project pay-offs are independent across firms. The support of the aggregate shock is $[\underline{\theta}, 1/p_{\max}]$, with $\underline{\theta} \in (0, 1)$, and its distribution $F(\theta)$ satisfies $E[\theta] = 1$.

Hence, for a given aggregate shock θ, the pay-off of the banks' portfolio of debt at $t = 1$ is $\theta p_0 b_0$. The pay-off of the banks' assets is thus increasing in θ, with a minimum for $\theta = \underline{\theta}$. Crucially, while the lowest pay-off at $t = 1$ of each of the debt contracts issued by the firm is zero, the diversification of idiosyncratic firm risks accomplished in the bank's balance sheet renders the lowest pay-off of its assets strictly positive. This allows the bank to issue some deposits that are safe without the need of insurance from the government, and constitutes the rationale for bank intermediation between savers that demand safety and the firms in the model.

The presence of deposit insurance creates distortions that provide a rationale for bank regulation. We assume that the bank is subject to a risk-weighted *maximum leverage regulation* that states that its deposits cannot exceed a fraction κ_0 of the expected return of its assets. Notice that this regulation can be interpreted as a minimum capital requirement. Given the bank's balance sheet at $t = 0$, the leverage requirement is satisfied if:

$$d_0 \leq \kappa_0 p_0 b_0. \tag{6}$$

[9] If such costs consist of payments to workers, the assumption of no rents by workers is consistent with a competitive market for labour in which the wage coincides with the disutility from working.

To fix our ideas, we make the following assumption:

Assumption 3. *$d_0 = \kappa_0 p_0 b_0$ and $\kappa_0 = \underline{\theta}$.*

The assumption states two things. First, given the maximum leverage requirement κ_0, the bank's deposits d_0 equal the maximum amount allowed by regulation, that is, the leverage requirement is binding. Second, the maximum leverage requirement κ_0 has the maximum value $\underline{\theta}$ that allows the bank to totally repay deposits for all aggregate shocks at $t = 1$.

Summing up, Assumption 3 sets a benchmark no lockdown situation in which the expected cost of the deposit insurance for the government is zero. The bank plays no active role at $t = 0$, and its expected profits at $t = 1$, that we denote Π_0, are given by

$$\Pi_0 = E\left[(\theta p_0 b_0 - d_0)^+\right] = (1 - \underline{\theta})\, p_0 b_0. \tag{7}$$

4 Model set-up with a lockdown

We now describe the economy with a lockdown at $t = 0$. The only difference relative to the set-up described in the previous section is that the economic lockdown reduces firms revenues at $t = 0$ to $r_0 = 0$. The lockdown does not reduce the operating costs at $t = 0$, that remain equal to ρ. The lockdown thus results in a liquidity shortfall of size ρ for each firm.[10]

Assumption 2 implies that, if firms' risk remains at p_0 as in the no-lockdown situation, then it is socially efficient to continue the projects even with a lockdown. We make the following additional assumption:

Assumption 4. *$\underline{\theta} p_0 b_0 < R < p_0 b_0$.*

The assumption has two implications regarding a potential firm bankruptcy at $t = 0$ in the lockdown economy. First, the projects' recovery value R allows to repay partially the debt to the bank b_0, which satisfies $b_0 > p_0 b_0$, and the entrepreneur obtains no value so that he always finds optimal to attempt to continue the project. Second, in case all firms enter into bankruptcy, the value obtained by the bank R is sufficient to repay entirely its deposits ($d_0 = \underline{\theta} p_0 b_0$, from Assumptions 3), but is lower than the expected payoff the bank obtained

[10] All our results would hold in a situation in which the elasticity of operating expenses to a fall in revenues is lower than one, so that the firms' face a cash shortfall.

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from its assets in the no lockdown benchmark $p_0 b_0$. [11]

From Assumption 4 we have that firms want to continue their projects and to pay for their operating expenditures ρ so they will attempt to borrow additional funds from the bank. This increases firms' overall debt and aggravates moral hazard problems in effort, making the projects less profitable and reducing expected output in the economy (Lemma 1). In this context, we consider a government whose objective is to limit output losses and with access to some policies to support firms. The government can support firms both directly through transfers and indirectly through policies that affect firms funding cost from banks such as loan guarantees or changes in leverage requirements. We describe next formally the government support policies, the competitive financing of banks to firms, and the problem of a government with limits on fiscal expenditures.

Government support policies A government support policy, henceforth *support policy* for short, is described by a tuple $\Lambda = (\tau, \kappa, \gamma)$ consisting of:

- A government transfer to the firm of $\tau \leq \rho$ units of funds.
- A higher maximum bank leverage requirement $\kappa \geq \underline{\theta}$. Notice that an increase in the leverage requirement can be interpreted as a reduction in the bank's minimum capital requirement. Such increase may render the bank incapable of repaying entirely deposits following bad aggregate shocks and the insurance on deposits costly for the government.
- A government guarantee $\gamma \leq 1$ on the new financing of bank to firms by which the government covers a fraction γ of each firm's promises on new funding in case of firm's default.

We assume that the government has no capability to enforce debt repayments by firms, so that it cannot support firms by directly lending to them at a subsidized rate.

The competitive bank loan for the residual funding For a given support policy $\Lambda = (\tau, \kappa, \gamma)$, the firm needs $\rho - \tau$ units of additional funding from the bank to continue. Suppose the bank lends those funds to the firm in exchange of a promised repayment b_L at $t = 1$. The new debt promise b_L adds to the existing one b_0, so that from (3) the firm's risk

[11] The first inequality in Assumption 4 is only done for simplicity, as it ensures that the government has the possibility not to incur any cost. In addition, we have assumed that the distribution of the aggregate shock θdoes not change as a result of the lockdown. It is possible to prove that all our results would qualitatively hold if we were to allow such distribution to deteriorate (that is, both $\underline{\theta}$ and $E[\theta]$ to drop) provided Assumption 2 and the second inequality in Assumption 4 were to hold conditional on the new aggregate shock distribution.

choice is $\hat{p}\left(b_0+b_L\right)$. Notice that the firm's risk increases as a result of the additional debt, that is, $\hat{p}\left(b_0+b_L\right) < \hat{p}\left(b_0\right)$. Finally, the bank obtains the $\rho-\tau$ units of funds lent to the firm by issuing a commensurate amount of new deposits.

For a given support policy $\Lambda = (\tau, \kappa, \gamma)$, we say that a bank loan for the residual financing, which is characterized by the promise b_L, is *feasible* if it satisfies the following constraints:

- The bank satisfies the new leverage requirement:

$$d_0+\rho-\tau \leq \gamma b_L+\kappa \hat{p}\left(b_0+b_L\right)\left(b_0+(1-\gamma)\, b_L\right). \tag{8}$$

  The LHS of the inequality above includes the bank's new deposits $(\rho-\tau)$. The RHS is the sum of two terms. The first one captures the amount of deposits the bank can issue against its guaranteed assets, and is the product of the fractional guarantee γ and the new debt promise b_L. Notice that we assume that the guaranteed part of the assets can back deposit issuance on a one-to-one basis, which is consistent with existent regulatory standards that assign a capital requirement on the publicly guaranteed fraction of the loans equal to zero. The second term captures the amount of deposits that can be issued against the non-guaranteed assets. It is the product of the new leverage requirement (κ), the expected value of the bank's assets taking into account the firms' risk $(\hat{p}(b_0+b_L))$, and the non-guaranteed assets $(b_0+(1-\gamma)b_L)$. Notice that the leverage requirement establishes the fraction of the value of the bank's assets that can be funded through deposits, so that it captures the capability of the bank to provide liquidity to the firms out of its assets.

- The bank finds optimal to grant the new financing rather than refusing it and pushing firms into bankruptcy:

$$\Pi(b_L) \geq R-d_0, \tag{9}$$

  where $\Pi(b_L)$ denotes the bank's expected profits when new lending is granted

$$\Pi(b_L)=E\left[\left(\theta \hat{p}\left(b_0+b_L\right)\left(b_0+b_L\right)+\left(1-\theta \hat{p}\left(b_0+b_L\right)\right) \gamma\left(b_0+b_L\right)-d_0-\rho+\tau\right)^{+}\right]. \tag{10}$$

  The participation condition (9) takes into account that Assumption 4 implies that in case of bankruptcy of all firms the bank seizes their entire recovery value R, and that after repaying its deposits the bankers obtain $R-d_0>0$.

Finally, whenever a feasible bank loan b_L for the residual financing exists given a policy Λ, we define the *competitive bank loan* $b_L^*(\Lambda)$ as the feasible loan with lowest b_L. Notice that such loan is trivially the one maximizing the firms' profits. We can show formally that the

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competitive bank loan arises as the equilibrium of a bargaining game between the bank, the firms and a potential new bank entrant with access to insured deposits and subject to the loan guarantees and leverage regulation defined by the support policy Λ.

The cost for the government of a support policy Let Λ be a support policy such that a feasible residual financing loan exists and let $b_L^*(\Lambda)$ denote the competitive one. The government faces a disbursement at $t = 0$ stemming from the transfer to the firm and may face disbursements at $t = 1$ from the loan and deposit guarantees. For each aggregate shock θ the total disbursement for the government is denoted $C(\Lambda|\theta)$ and amounts to:

$$C(\Lambda|\theta) = \tau + (1 - \theta p^*)\,\gamma(b_0 + b_L^*) + \left(d_0 + \rho - \tau - \theta p^*(b_0 + b_L^*) - (1 - \theta p^*)\gamma(b_0 + b_L^*)\right)^+ , \tag{11}$$

where we have denoted $b_L^* = b_L^*(\Lambda)$ and $p^* = \hat{p}(b_0 + b_L^*)$. The terms in the expression above represent the transfer to the firms at $t = 0$, the disbursement for the loan guarantees at $t = 1$ and the expenditure in deposit guarantees at $t = 1$. Notice that when the bank fails at $t = 1$ the loan guarantees allow to reduce the cost of the insurance on deposits. Finally, the expected cost of the support policy Λ is given by $E[C(\Lambda|\theta)]$.

For a support policy Λ such that the residual financing is not feasible, there is liquidation of all firms. Assumption 4 implies that the bank deposits at $t = 0$ would be repaid in full and the cost for the government would be $E[C(\Lambda|\theta)] = 0$.

The government optimal support policy problem Consider a government that can spend in expectation at most X units of funds. The government problem is that of choosing the support policy Λ satisfying $E[C(\Lambda|\theta)] \leq X$ that maximizes aggregate welfare, which consists in the sum of the expected utility of firms, the bank, the bank depositors (old and potentially new) and the government. In this optimal policy problem, the government anticipates whether an intervention leads to the continuation of the firms or not. Notice that Assumption 4 implies that under the policy $\Lambda_0 = (\tau = 0, \kappa = \underline{\theta}, \gamma = 0)$, that can be interpreted as a no intervention policy, we have that $E[C(\Lambda_0|\theta)] = 0$, regardless of whether this intervention leads to continuation or not. Hence, the set of support policies compatible with the government's budget is never empty.

5 Optimal mix of firm transfers and leverage requirements

In this section, we restrict our attention to government policies that consist of a direct transfer to firms and a relaxation of leverage requirements, but do not include guarantees

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to new bank loans. That is, we consider interventions $\Lambda = (\tau, \kappa, \gamma)$ with $\gamma = 0$, that for the sake of compactness we refer to as (τ, κ) interventions.

The analysis in this section is organized as follows. We first describe the competitive equilibrium for the residual bank financing to the firm for a given (τ, κ) intervention. We then describe the optimal combination of the two policy tools as a function of the expected public cost of the intervention. Finally, in the next section, we will show that adding loan guarantees γ to the (τ, κ) intervention toolkit never allows to improve welfare.

5.1 The competitive bank residual financing

Consider a (τ, κ) intervention with $\tau \geq 0, \kappa \geq \underline{\theta}$. We characterize in this section when the bank provides residual financing to the firms, and, in that case, the competitive promised repayment $b_L^*(\tau, \kappa)$ at $t = 1$ the bank requires in order to provide the residual financing $\rho - \tau$ needed by the firm at $t = 0$. Recall that the competitive promise b_L^* is the minimum value b_L satisfying both the bank's maximum leverage constraint in (8), that states that at most a fraction κ of the expected value of the bank's assets can back the issuance of deposits, and the banks' participation constraint in (9), that sets a lower bound on the bank's profits stemming from their option to refuse to lend and seize the recovery value of the firms.

Using Assumption 3, the leverage constraint (8) for some promise b_L can be rewritten as:

$$\rho - \tau \leq \underline{\theta} \left[\hat{p} \left(b_0 + b_L \right) \left(b_0 + b_L \right) - \hat{p} \left(b_0 \right) b_0 \right] + \left(\kappa - \underline{\theta} \right) \hat{p} \left(b_0 + b_L \right) \left(b_0 + b_L \right). \tag{12}$$

The inequality above can be interpreted as the bank's *lending constraint.* The LHS captures the new deposits the bank has to issue in order to satisfy firms' liquidity needs. The RHS exhibits how the bank can fund those deposits, taking into account that it had originally issued as much deposits as possible. The expression includes two terms. The first one captures the additional deposits the bank can issue due to the variation in the expected value of its assets stemming from the new lending if the leverage requirement remained fixed at $\underline{\theta}$. Notice from Lemma 1 that such term is positive provided $b_L \in [0, b_{\max} - b_0]$. The second term captures the amount of new deposits the bank can issue as a result of an increase in the maximum leverage requirement from $\underline{\theta}$ to κ.

The next result follows.

Lemma 2. *Let ρ be the firms' operating cost. There exists a lending function $\overline{L}(\kappa)$ such that for an intervention policy (τ, κ) the bank is able to grant the residual financing to the firms if and only if $\rho - \tau \leq \overline{L}(\kappa)$. The function $\overline{L}(\kappa)$ is strictly increasing in κ and $\overline{L}(\underline{\theta}) > 0$. In addition, if the bank is able and finds optimal to grant new lending then the competitive promise $b_L^*(\tau, \kappa)$ is such that either the bank's maximum leverage constraint in (8) or the banks' participation constraint in (9)*

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are binding.

The lemma states that there exists a maximum amount of residual financing the bank can grant to the firms. This lending capability of the bank is given by a function $\overline{L}(\kappa)$ that is increasing in the leverage requirement. In addition, the lemma states that the competitive promise for the residual financing of the firms makes either the bank's maximum leverage constraint or its participation constraint binding. This result can be interpreted as saying that competition leads the bank to offer financing as cheap as compatible with its liquidity constraint unless that would result in lower profits than under the liquidation of the firms.

Consider an operating cost and intervention policy satisfying $\rho - \tau \leq \overline{L}(\kappa)$, so that from Lemma 2 the bank has sufficient lending capacity to provide the residual financing to the firms. We next analyze whether the bank finds optimal to grant the new lending, and if so, which are the properties of the competitive promise.

Suppose that an intervention (τ, κ) satisfies $\rho - \tau \leq \overline{L}(\kappa)$. Suppose that the bank finds optimal to grant new lending and let $b_L^*(\tau, \kappa)$ denote the associated competitive promise. Suppose in addition that the bank's leverage requirement in (8), or equivalently in (12), is binding. Using this equality, we have that the expression for the bank's expected profits in (10) can be rewritten as

$$\begin{aligned} \Pi(b_L^*(\tau,\kappa)|\rho) &= E\left[\left(\theta\hat{p}\left(b_0 + b_L^*(\tau,\kappa)\right)\left(b_0 + b_L^*(\tau,\kappa)\right) - \left(d_0 + \rho - \tau\right)\right)^+\right] && (13) \\ &= E\left[\left(\theta\frac{d_0 + \rho - \tau}{\kappa} - \left(d_0 + \rho - \tau\right)\right)^+\right], && (14) \end{aligned}$$

so that we have the following compact expression for the bank's profits as a function of the intervention (τ, κ) :

$$\Pi(\tau,\kappa|\rho) = (d_0 + \rho - \tau)\,\frac{E\left[(\theta - \kappa)^+\right]}{\kappa}. \qquad (15)$$

The expression shows that when the leverage requirements is binding, the bank's profits amount to the product of its deposits $(d_0 + \rho - \tau)$ and a term that captures the rents the bank obtains from each unit of deposits $(E[(\theta - \kappa)^+]/\kappa)$. Notice that the first term only depends on the firms' residual financing needs $\rho - \tau$ and the second term on the leverage requirement κ. In particular, the expression in (15) implies that, for given leverage requirement, the bank's profits are increasing in the residual financing $\rho - \tau$ demanded by firms because the lending constraint faced by the bank prevents competition from reducing to zero the rents the bank obtains. In addition, the rents per unit of deposit obtained by the bank are decreasing in the maximum leverage requirement κ. The intuition is that the relaxation of leverage requirements expands the supply of lending by the bank (equation (12)), allowing the competitive bank to reduce the promise b_L^*, and leading to a reduction in the bank's profits.

To gain more intuition on the effects of the intervention on the bank's profits, we can rewrite (15) as:

$$\Pi(\tau,\kappa|\rho) = \Pi_0 + (\rho-\tau)\frac{E\left[(\theta-\kappa)^+\right]}{\kappa} - d_0\left(\frac{1-\underline{\theta}}{\underline{\theta}} - \frac{E\left[(\theta-\kappa)^+\right]}{\kappa}\right), \tag{16}$$

where Π_0 are the bank's expected profits in the no-lockdown economy described in (7). The expression above represents the bank's profits as the sum of the profits in the no-lockdown economy, the rents obtained in the new financing provided to the firms given the new leverage requirement, and the reduction in the rents the bank obtains from its legacy deposits due to the increase in the maximum leverage requirement.

Notice that Assumption 4 implies that $\Pi_0 > R - d_0$. From (16), we have that the bank's participation constraint (9) is strictly satisfied if the leverage requirement κ is close to $\underline{\theta}$, which would confirm our initial assumption that the leverage requirement (8) was binding. This proves that for an intervention (τ,κ) with low residual financing needs and low relaxation of leverage requirements ($\rho-\tau \le \overline{L}(\kappa)$ and κ close to $\underline{\theta}$) the bank is able and finds optimal to grant new lending and the leverage requirement is binding.

However, as κ increases from that situation we have from (15) (or (16)), that the bank's profits get reduced as a result of a relaxation of lending constraints. If κ is sufficiently large, inequality (9) might not be satisfied for the value of b_L that makes (16) binding. When that happens, the competitive b_L^* is the one for which the participation constraint (16) is binding but the lending constraint (16) is not. Further increases in the leverage requirement do not lead to a reduction in b_L^*. Thus, there is a limit to the support that can be given to firms by relaxing the leverage requirement stemming from the bank's unwillingness to pass additional deposit issuance capability into cheaper financing to firms.

The next proposition builds on these intuitions and provides a formal statement of the results in this section.

Proposition 1. *Let $\overline{L}_{PC} > 0$ be the constant defined by the equality*

$$E\left[\left(\theta\hat{p}\left(b_{max}\right)b_{max} - d_0 - \overline{L}_{PC}\right)^+\right] = R - d_0. \tag{17}$$

There exist two increasing functions $\underline{\kappa}(z), \overline{\kappa}(z) \in [\underline{\theta}, \overline{\theta})$ defined in the interval $z \in [0, \overline{L}_{PC}]$, with $\underline{\kappa}(z) < \overline{\kappa}(z)$ for $z < \overline{L}_{PC}$ and $\underline{\kappa}(z) = \underline{\theta}$ for z in a neighborhood of zero, such that interventions (τ,κ) lay in one of these regions:

- *If $\rho-\tau > \overline{L}_{PC}$ or $\kappa < \underline{\kappa}(\rho-\tau)$: Firms do not obtain bank lending and are liquidated.*

- *If* $\rho - \tau \leq \overline{L}_{PC}$ *and* $\kappa \in [\underline{\kappa}(\rho-\tau), \overline{\kappa}(\rho-\tau)]$*: Firms obtain bank lending and the bank's leverage requirement is binding. The competitive promise* $b_L^*(\tau,\kappa)$ *and the bank's profits* $\Pi(\tau,\kappa)$ *are strictly decreasing in* τ *and* κ*.*
- *If* $\rho - \tau \leq \overline{L}_{PC}$ *and* $\kappa > \overline{\kappa}(\rho-\tau)$*: Firms obtain bank lending and the bank's leverage requirement is not binding. The variable* $b_L^*(\tau,\kappa)$ *is strictly decreasing in* τ *and constant in* κ*, and* $\Pi(\tau,\kappa) = R - d_0$*.*

The proposition describes how intervention policies affect firms' access to bank's financing given their residual financing needs. The amount of (residual) private financing that firms can get is limited by either the ability of the bank to raise new deposits (lending constraint (LC)) or by its willingness to provide lending (participation constraint (PC)). The results are illustrated in Figure 1, which exhibits the outcomes of (τ,κ) interventions. Notice that for convenience the horizontal axes represents the residual financing needs $\rho - \tau$ given an intervention.. Firms obtain financing only in the colored regions. In fact, the red line represents the minimum leverage such that the bank's LC is satisfied given some residual financing needs.[12] The green line instead represents the maximum leverage compatible with the bank's PC. Hence in the purple region, the leverage requirement is large enough to grant banks' sufficient lending capability to satisfy firms' residual financing needs, but not too large so that banks can chooses maximum leverage and still obtain some profits relative to liquidation. As the maximum leverage requirement κ increases in this purple region, the associated competitive promise $b_L^*(\tau,\kappa)$ and bank profits go down. If the maximum leverage requirement increases further, the economy enters into the green region, in which the bank's LC becomes slack. The reason is that if the bank were to choose maximum leverage, the financing to firms would be so cheap that the bank's PC would not be satisfied. An increase in κ in this green region, has no effect on bank's leverage nor on b_L^*. Notice finally that in the rightward white region in which the red line is above the green line the leverage requirement is loose enough to grant the bank sufficient capability to lend to firms, but the bank finds optimal not to lend and the firms are liquidated.

5.2 Optimal policy mix

We now consider the problem of a government that aims at maximizing social welfare and can intervene with policies (τ,κ) under the restriction that their expected cost cannot exceed some given amount $X \geq 0$, that we refer to as the government's budget. We define social welfare in this economy as the sum of the expected utility of all the agents: firms, the bank, the existing and potentially new depositors, and the government.

[12]The minimum leverage function $\underline{\kappa}(\rho-\tau)$ represents the inverse of the lending function $\overline{L}(\kappa)$ from Lemma 2.

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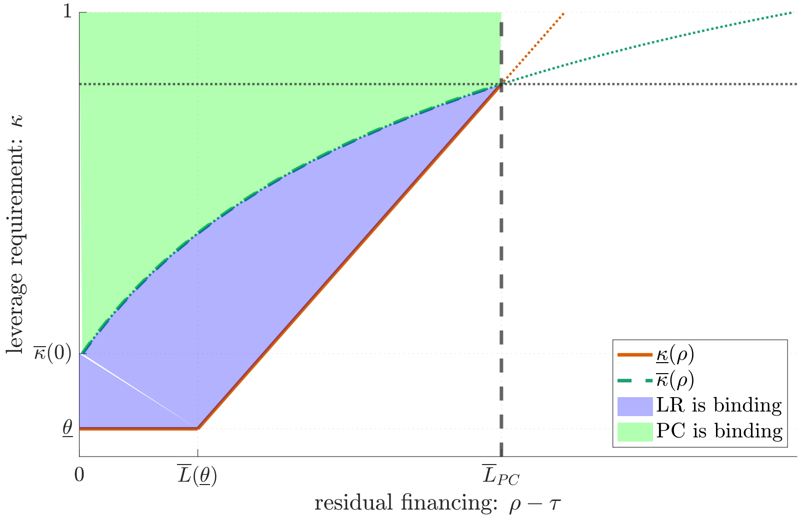
Figure 1: Leverage requirement and residual financing



Notes: Illustration of regions in Proposition 1. LC refers to the lending constraint (12) , while PC refers to the participation constraint (9).

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Let (τ, κ) be an intervention. If firms are able to obtain financing, which from Proposition 1 happens when $\rho - \tau \leq \overline{L}_{PC}$ and $\kappa \geq \underline{\kappa}(\rho - \tau)$, social welfare under continuation denoted $Y_C(\tau, \kappa)$ equals

$$Y_C(\tau,\kappa) = [p^*(\tau,\kappa)\left(A - b_0 - b_L^*(\tau,\kappa)\right)) - c(p^*(\tau,\kappa))] + \Pi\left(b_L^*(\tau,\kappa)\right) + d_0 - E[C(\tau,\kappa|\theta)], \tag{18}$$

where $p^*(\tau, \kappa) = \hat{p}(b_0 + b_L^*(\tau, \kappa))$. The first three terms in (18) represent the profits of firms, the bank, and initial depositors obtained by continuing the project at $t = 1$, respectively. The last term is the cost of the government due to the expected disbursements at $t = 0$ and $t = 1$, whose expression is given in (11). Notice that the expression does not include new depositors, which obtain zero utility from their lending: their consumption is reduced at $t = 0$ by $\rho - \tau$, and increases at $t = 1$ by the same amount. Replacing (11) and (13) into (18), we can express welfare as:

$$Y_C(\tau,\kappa) = \hat{p}(b_0 + b_L^*(\tau,\kappa))A - c(\hat{p}(b_0 + b_L^*(\tau,\kappa))) - \rho. \tag{19}$$

This compact expression results from three observations: *i)* at $t = 0$ the operating cost ρ is incurred and is financed with a transfer τ from the government and new deposits $\rho - \tau$, that lead to an overall reduction in utility at that date equal to ρ; *ii)* between $t = 0$ and $t = 1$ entrepreneurs exert effort, which leads to some disutility; and *iii)* at $t = 1$ the overall utility derived by firms, the bank and the (old and new) depositors amounts to the total output of the project plus the transfers from the government to satisfy the insurance on deposits, and the latter reduce amount to a redistribution of utility between depositors and the government. Notice that social welfare in case of continuation only depends on the risk-choice $\hat{p}(b_0 + b_L^*(\tau, \kappa))$ of the firms which in turn is determined by $b_L^*(\tau, \kappa)$, and welfare is strictly decreasing in this variable.

In case of firms' liquidation, which from Proposition 1 happens when $\rho - \tau > \overline{L}_{PC}$ or $\kappa < \underline{\kappa}(\rho - \tau)$, social welfare amounts to the recovery value R of the projects. From Assumption 4 the cost for the government is zero.

In general, social welfare, which we denote $Y(\tau, \kappa)$, is given by:

$$Y(\tau,\kappa) = \begin{cases} Y_C(\tau,\kappa) & \text{if } \rho - \tau \leq \overline{L}_{PC} \text{ and } \kappa \geq \underline{\kappa}(\rho - \tau) \\ R & \text{otherwise} \end{cases}. \tag{20}$$

The government's problem can thus be written as following maximization problem:

$$\begin{aligned} &\max_{(\tau,\kappa)} \; Y(\tau,\kappa) \\ &\text{s.t. } E[C(\tau,\kappa|\theta)] \leq X. \end{aligned} \tag{21}$$

We focus hence on the interesting situation in which there exist interventions satisfying the budget constraint that induce the firms' continuation. To gain more intuition, consider an intervention (τ, κ) with $\rho - \tau < \overline{L}_{PC}$ and $\kappa \in [\underline{\kappa}(\rho - \tau), \overline{\kappa}(\rho - \tau))$, so that it belongs to region 2 of Proposition 1 in which firms' obtain the bank residual financing and the leverage constraint (8) is binding. We have that

$$d_0 + \rho - \tau = \kappa \hat{p} \left(b_0 + b_L^*(\tau, \kappa) \right) \left(b_0 + b_L^*(\tau, \kappa) \right). \tag{22}$$

and using (11) and (22), we can write

$$E[C(\Lambda|\theta)] = \tau + (d_0 + \rho - \tau) \, E\left[\frac{(\kappa - \theta)^+}{\kappa} \right]. \tag{23}$$

The expression exhibits the government cost as the sum of the transfer τ at $t = 0$, and the expected cost of the insurance at $t = 1$ on the overall amount of deposits $d_0 + \rho - \tau$. Notice that the term $E\left[(\kappa - \theta)^+ / \kappa\right]$ can be interpreted as the per unit cost of deposit insurance, and shows that the government only has to partially repay deposits for bad enough aggregate shocks, that is for $\theta < \kappa$.

The per unit cost of deposit insurance increases as the leverage requirement is loosened (provided the leverage constraint is binding). It also gives the bank additional loss-absorption capacity against bad aggregate shocks that allows the bank to raise additional funds from depositors and channel them to firms, reducing the need of direct transfers at $t = 0$. In fact, isolating τ in (22) and replacing into (23), we have that in region 2 of Proposition 1 the expected cost for the government can be written as the following function of b_L^* and κ:

$$E[C(\Lambda|\theta)] = d_0 + \rho - \hat{p} \left(b_0 + b_L^* \right) \left(b_0 + b_L^* \right) \left(\kappa - E\left[(\kappa - \theta)^+ \right] \right). \tag{24}$$

Recall from (19) that welfare is determined by the competitive promise b_L^*. We immediately have from the expression above that, for a given b_L^* and thus welfare, the expected cost for the government is decreasing in the leverage requirement.[13] The intuition is as follows. The safe collateral that the bank creates out of its lending to firms is determined by the given promise b_L^*. It amounts to $\underline{\theta} \hat{p} \left(b_0 + b_L^* \right) \left(b_0 + b_L^* \right)$ and it is insufficient to meet the safe collateral amounting to $d_0 + \rho$ that is needed to allow the firms' continuation. The shortfall must be provided by the government, either through uncontingent transfers at $t = 0$ or through transfers contingent on bad shocks at $t = 1$. The increase in the leverage requirement allows the government to substitute some of the uncontingent transfers with contingent ones, which by definition have a lower expected cost as they are incurred with probability less than one. Therefore, allowing the bank to operate with a larger leverage

[13]Notice that $\mathrm{d}(\kappa - E[(\kappa - \theta)^+]/\mathrm{d}\kappa > 0$.

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that increases the expected bill on deposit insurance constitutes for the government a better bang for the buck than direct transfers to firms and would be the preferred policy. However, this requires banks to be willing to increase their leverage as they are increasingly allowed to, and Proposition 1 states that this might not be the case when the leverage requirement has attained a sufficiently high level.

Building on these intuitions we can prove the following proposition.

Proposition 2. *Let $X > 0$ be the government budget. There exist thresholds $\underline{X}(\rho), \overline{X}(\rho)$ with $0 \leq \underline{X}(\rho) \leq \overline{X}(\rho)$ and $\underline{X}(\rho) = 0$ in a neighborhood of zero and $\underline{X}(\rho) = \overline{X}(\rho)$ for $\rho \geq \overline{L}_{PC}$ such that the optimal intervention $(\tau^*(X), \kappa^*(X))$ satisfies:*

- *if $X \leq \underline{X}(\rho)$: firms are liquidated and the optimal policy consists of no intervention $(\tau^*(X) = 0, \kappa^*(X) = \underline{\theta})$. The government cost is zero.*
- *if $X \in (\underline{X}(\rho), \overline{X}(\rho))$: firms continue and the optimal policy only includes an increase in the leverage requirement $(\tau^*(X) = 0, \kappa^*(X) \in (\underline{\theta}, \overline{\kappa}(\rho)))$. The government cost is X, and $\kappa^*(X)$ is increasing in X.*
- *if $X > \overline{X}(\rho)$: firms continue and the optimal policies exhibit a fixed strictly positive transfer and a leverage requirement above a threshold $(\tau^*(X) > 0, \kappa^*(X) \geq \overline{\kappa}(\rho - \tau^*(X)))$. The government cost is X, $\tau^*(X)$ is increasing in X, and the leverage chosen by banks is $\overline{\kappa}(\rho - \tau^*(X))$ which is decreasing in X.*

Finally, the welfare induced by the optimal policy is strictly increasing and concave in X for $X > \underline{X}(\rho)$.

The proposition provides a *pecking order* in the use of the intervention toolkit (τ, κ) depending on the size X of the government's budget. Figure 2 illustrates the results in the proposition. Panel 2a shows the welfare loss relative to the no lockdown scenario, Panel 2b shows the new loan promise associated with the intervention, Panel 2c shows the bank profits, and Panel 2d the bank debt to asset ratio. Each of the figures compares the equilibrium with the optimal policy versus an intervention that relies solely on transfers. The figure exhibits a numerical illustration in which in which the operating cost ρ is high enough so that in absence of intervention firms are liquidated. The proposition states that there are generically three optimal intervention regions. When the government budget is low ($X < \underline{X}$), the government does not intervene and the firms are liquidated.[14] When the budget is medium ($X \in (\underline{X}, \overline{X})$), the government finds optimal to intervene but uses only the loosening of the leverage requirement. While firms are able to continue, they end-up with high debt (see panel 2b), which amplifies the direct cash-flow loss ρ implied by the

[14]This region does not exist if ρ is low enough so that firms are able to continue even without intervention.

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lockdown due to the induced moral hazard (see panel 2a). As the government budget increases in this region, the optimal κ increases and banks find optimal to expand their leverage as much as they are allowed to (see panel 2d). The government's budget constraint is binding and all the government disbursements are associated with the increasing contingent liabilities implied by the insurance on deposits that are backed by a lower overall promise from firms to banks. As panel 2b shows, the financing of the operating costs arrives at better terms to the firms thanks to the willingness of the government to incur the larger cost on deposit insurance, which expands the supply of lending. The bank's profits in this region decrease because with higher lending capacity, the competitive environment leads to a reduction in the scarcity rents associated with intermediation (see Panel 2c). The cheaper financing implies firms end-up less indebted, which reduces the moral hazard and improves expected output (see in Panel 2a). When the government budget is high $X > \overline{X}$, then the optimal intervention also includes transfers to firms. The reason is that leverage loosening becomes ineffective because the bank is at its participation constraint. As the government budget further increases, transfers to firms also increase, which reduces the residual financing provided by the bank. For fixed leverage, this pushes down the bank's profits, and leads in equilibrium the bank to reduce its leverage. As the government budget increases in this region, welfare in the economy increases as a result of the reduction of the overall indebtedness of firms, but at a lower pace because a larger fraction of the support is given with uncontingent transfers instead of with contingent payments for deposit insurance.

Finally, the figure shows that using only transfers is a suboptimal policy. First, the budget needed in order to support firms enough so that they can continue is larger. Second, as long as the budget is not enough to finance the whole firm operational cost ($X < \rho$), that policy, relative to the optimal one, implies firms end-up more indebted (see panel 2b) and banks make more profits (see panel 2c), which induces a lower welfare (see panel 2a).

The possibility of suboptimal zombie lending We conclude this section with a brief discussion of the possibility that suboptimal government interventions may lead to zombie lending, that is, to the inefficient continuation of firms. Recall that Assumption 2 implies that in the no lockdown economy the continuation of the firms is efficient. In addition, in absence of intervention in the lockdown economy, continuation is socially efficient whenever the bank finds optimal to provide the financing of the operating costs because the bank has the option to push firms into liquidation and there are no distortions associated with deposit insurance ($\kappa = \underline{\theta}$). So, despite the increase in project risk, continuation is socially efficient when it is feasible if there is no intervention.

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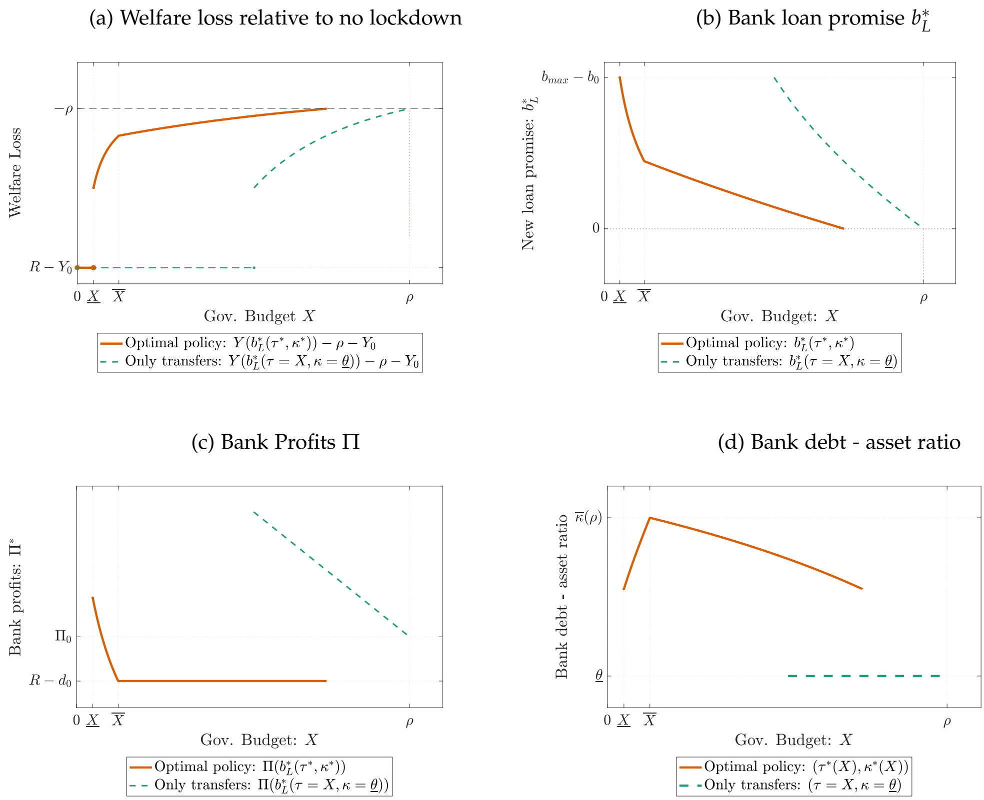
Figure 2: Welfare and loan promise given government budget X



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This might not be the case when the government provides support because the transfers from the government to the firms and the subsidy on deposits may create a wedge between the private and social benefits from continuation. In fact, (20) shows that for a policy (τ, κ) that induces continuation, we have that continuation is socially efficient if and only if

$$p^*(\tau, \kappa)A - c\left(p^*(\tau, \kappa)\right) - \rho \geq R.$$

Notice that while the inequality above is satisfied for the no-lockdown risk choice p_0 from Assumption 2, it might not be satisfied if $p^*(\tau, \kappa)$ is sufficiently below p_0.

The next lemma states when that might happen.

Lemma 3. *Suppose that $\hat{p}(b_{max})A - c(\hat{p}(b_{max})) - \overline{L}_{PC} < R$. Then, there exists a threshold $\tilde{\rho} > 0$, such that for $\rho > \tilde{\rho}$ there exist intervention policies that induce socially inefficient continuation. The government cost associated with those policies is positive but below the government threshold $\underline{X}(\rho)$ defined in Proposition 2.*

The lemma states that when the operating cost is sufficiently high, a government with a low budget may be able to induce the inefficient continuation of the firms. Of course, this form of government supported zombie lending would be suboptimal. In those cases, social welfare would increase with a no intervention policy that pushes firms into liquidation (and would have no cost for the government). The results highlight nevertheless the need to allocate a sufficiently large budget to the intervention in order for them to be welfare improving.

6 Equilibrium with Loan Guarantees

We now analyze general government interventions $\Lambda = (\tau, \kappa, \gamma)$ that also include a loan guarantee γ. We find that adding this third policy to the (τ, κ) intervention toolkit never leads to strict improvements in welfare. We also characterize when loan guarantees constitute a substitute to direct transfers to firms.

We start the analysis by describing the role played by loan guarantees in this economy. The analysis reproduces some of the arguments conducted in Section 5, so that in the interest of space we skip intermediate formal steps. For an intervention $\Lambda = (\tau, \kappa, \gamma)$, the leverage constraint (8) can be written as:

$$\rho - \tau \leq \underline{\theta}\left[\hat{p}\left(b_0 + b_L\right)\left(b_0 + b_L\right) - \hat{p}\left(b_0\right)b_0\right] + \left(\kappa - \underline{\theta}\right)\hat{p}\left(b_0 + b_L\right)\left(b_0 + b_L\right) + \\ + \left(1 - \kappa\hat{p}(b_0 + b_L)\right)\gamma b_L, \quad (25)$$

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which extends the bank's *liquidity constraint* in (12) by including the amount of new deposits the bank can issue as a result of the guarantees. By providing loan guarantees, the government increases the default value of loans and increases the bank capacity to provide liquidity.

Consider an intervention Λ that induces firms to continue and let $b_L^*(\Lambda)$ denote the competitive promise for the residual bank financing. An analogous to Lemma 2 states that either the bank's liquidity constraint (25) or the bank's participation constraint (9) are binding for $b_L^*(\Lambda)$.

Suppose the liquidity constraint is binding. We have from (25), or equivalently from (8), that as the loan guarantee γ increases, the competitive promise $b_L^*(\Lambda)$ falls, but the guaranteed loan payoff $\gamma b_L^*(\Lambda)$ increases. We have in addition from (10) and (25) that the bank's expected profits can be written as

$$\Pi(\Lambda|\rho) = (d_0 + \rho - \tau - \gamma b_L^*(\Lambda)) \frac{E\left[(\theta - \kappa)^+\right]}{\kappa}, \tag{26}$$

which extends the expression in (15). Notice that an increase in loan guarantees γ reduces the bank's profits. The intuition is as follows. On the one hand, for a given promise b_L^*, the bank benefits from the loan guarantees since the default payoff of its assets increases. On the other hand, the introduction of guarantees relaxes the leverage constraint of the bank and expands the supply of liquidity, reducing the competitive promise b_L^* and the success value of the bank assets. This general equilibrium effect reduces bank profits and expression (26) shows that it is the dominating effect.

Following the same intuitions as in the previous section, we have that when $\tau < \rho$, κ is close to $\underline{\theta}$ and γ is low, then $\Pi(\Lambda|\rho) > \Pi_0 > R - d_0$ and the bank's participation constraint is strictly satisfied, which confirms our initial assumption that the leverage requirement is binding. In these situations the bank's profits are higher than in the no lockdown case because the bank obtains some intermediation rents from the provision of additional liquidity to firms (and despite the reduction in the quality of its outstanding loans).

The pecking order In the previous section, we have shown that there is a pecking order in the use of the (τ, κ) toolkit that states that if the leverage constraint is binding in an optimal intervention then $\tau = 0$. We next intuitively argue why this pecking order extends also to the Λ toolkit.

Consider a single policy intervention $\Lambda_\kappa = (\tau = 0, \kappa > \underline{\theta}, \gamma = 0)$ that induces the bank's liquidity constraint to be binding. Denote $b_L^* = b_L^*(\Lambda_\kappa)$, $p^* = \hat{p}(b_0 + b_L^*)$. From (23) we have that the expected government cost is

$$E[C(\Lambda_\kappa|\theta)] = (d_0 + \rho)\frac{E\left[(\kappa - \theta)^+\right]}{\kappa} = p^*(b_0 + b_L^*)E\left[(\kappa - \theta)^+\right], \tag{27}$$

where the last equality follows from (22).

Let us suppose that there exists a single policy intervention $\Lambda_\gamma = (\tau = 0, \kappa = \underline{\theta}, \gamma > 0)$ that induces the same b_L^*. Suppose that under this intervention the liquidity constraint (25) is also binding. We have thus by construction that

$$(\kappa - \underline{\theta})\, p^*(b_0 + b_L^*) = \gamma b_L^*(1 - \underline{\theta} p^*). \tag{28}$$

We have from (11) and using that under Λ_γ the bank never defaults, that the expected cost associated with this policy would be

$$E[C(\Lambda_\gamma|\theta)] = E\left[\gamma b_L^*\left(1 - \theta p^*\right)\right] = \gamma b_L^*\left(1 - p^*\right). \tag{29}$$

We have from (27), (28) and (29) that:

$$E[C(\Lambda_\gamma|\theta)] = (\kappa - \underline{\theta})\, p^*(b_0 + b_L^*)\frac{1 - p^*}{1 - \underline{\theta} p^*} > (\kappa - \underline{\theta})\, p^*(b_0 + b_L^*) > E[C(\Lambda_\kappa|\theta)]. \tag{30}$$

The inequality states that the intervention that relies only on loan guarantees Λ_γ is strictly more expensive than that one that relies only on a loosening of leverage requirements Λ_κ. Notice that by construction the two interventions lead to the same disbursement for the government under the worst aggregate shock $\theta = \underline{\theta}$, as this disbursement determines the competitive promise b_L^*. Yet, the loan guarantee intervention leads to a strictly larger disbursement than the leverage loosening intervention for any other aggregate shock $\theta > \underline{\theta}$. The reason is that the leverage loosening intervention only gives rise to disbursements to satisfy a shortfall between the payoff of the bank's assets and its overall amount of deposits, so that by definition leads to the minimum disbursement that ensures the safety of the deposits. Loan guarantees are instead a less targeted way of increasing the ability of the bank to raise deposits, which increases the cost for the government. In fact, due to the presence of idiosyncratic firm risk, loan guarantees imply a government disbursement even when the aggregate shock is large and the bank makes profits at the final date.

Finally, notice that for interventions Λ that lead to continuation, the welfare decomposition expression in (18) and the compact welfare expression in (19) remain valid after replacing (τ, κ) with Λ. Combining the two expressions we immediately have that

$$\Pi(\Lambda_\gamma|\rho) - \Pi(\Lambda_\kappa|\rho) = -\left(E[C(\Lambda_\gamma|\theta)] - E[C(\Lambda_\kappa|\theta)]\right) > 0. \tag{31}$$

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The expression shows that the excess cost of the loan guarantees intervention relative to the leverage loosening intervention leads to a commensurate increase in the bank's profits.[15] This is because the two interventions lead by construction to the same welfare (defined by b_L^*) so the costs for the government translate into gains for the bank in a one-to-one basis.

Substitutability of direct transfers and loan guarantees We now consider a situation in which a general intervention Λ is such that the participation constraint (9) is binding and the liquidity constraint (25) is strictly slack. We must have in this case that

$$E\left[\left(\theta p^*(\Lambda)\left(b_0 + b_L^*(\Lambda)\right) + \left(1-\theta p^*(\Lambda)\right)\gamma b_L^*(\Lambda) - (d_0+\rho-\tau)\right)^+\right] = R - d_0, \tag{32}$$

where $p^*(\Lambda) = \hat{p}\left(b_0 + b_L^*(\Lambda)\right)$. It is possible to prove that the expression above determines the competitive promise $b_L^*(\Lambda)$ as a decreasing function of only τ and γ, that we denote as $b_L^*(\tau, \gamma)$. This confirms the result from the previous section that, when the bank's participation constraint becomes binding, increases in the maximum leverage requirement do not allow to provide further support to firms because the bank refrains from passing the additional leverage capability into cheaper financing to firms. Yet, increases in loan guarantees, analogously to transfers to firms, are passed to firms through a reduction in the competitive promise b_L^*. The reason why in this region increases in loan guarantees are still effective while increases in leverage requirements are not, stems from the fact that, besides increasing its liquidity capacity, the bank benefits directly from the guarantee. Notice from (32) that the profits are increasing in γ (for given b_L^*) due to the implied government transfers even during positive aggregate shocks. Thus, following an increase in γ, the bank would have incentives to keep lending and competition will lead to a reduction of b_L^*.

Using that (9) is binding, we have from the welfare expressions (18) and (19), that the expected cost of the intervention is given by:

$$E[C(\Lambda|\theta)] = R + \rho - \hat{p}(b_0 + b_L^*(\tau,\gamma))(b_0 + b_L^*(\tau,\gamma)), \tag{33}$$

where we have used that the competitive promise is a function $b_L^*(\tau,\gamma)$. We have thus that a marginal increase in loan guarantees γ accompanied with a marginal reduction of direct transfers τ such that the promise on residual financing $b_L^*(\tau,\gamma)$ remains constant does not affect neither welfare nor the expected cost for the government. The two policies are thus locally perfect substitutes, but not globally as we argue next.

[15]Notice the expression implies that the bank's participation constraint (9) is satisfied under the intervention Λ_γ as was initially assumed.

Transfers are strictly necessary We next argue that when both the size of the liquidity shock and of the government budget are large enough, positive direct transfers are part of any optimal Λ intervention. Loan guarantees are thus not a perfect substitute for transfers in these situations. The reason is that in order for the guarantees to be effective banks must increase their lending. So, that limits the ability of this policy to reduce the loan promise b_L.

In particular, we have that if the operational cost ρ is high enough then only using the loosening of the leverage requirement does not achieve that firms can continue and operate with an amount of debt equal to their pre-lockdown levels: $b_L^* = 0$. From (12), we see that this is the case if $\rho > (\overline{\kappa}(\rho) - \underline{\theta})p_0 b_0$. By combining the leverage requirement with enough transfers $\tau > \rho - (\overline{\kappa}(\rho - \tau) - \underline{\theta})p_0 b_0$, an optimal policy can achieve that firms continue at their pre-lockdown levels, so there is no amplification of the initial loss ρ. Instead, in the absence of transfers, even if we combine the maximum leverage requirement with full guarantees ($\gamma = 1$), a direct implication of (32) is that it would require firms operating at relatively higher debt levels: $b_L^*(\gamma = 1, \tau = 0) > 0$.

The next propositions provides a formal statement of the results intuitively discussed in this section.

Proposition 3. *The possibility to add loan guarantees γ to (τ, κ) interventions never strictly increases welfare. When the government budget X is large and the operational cost $\rho > (\overline{\kappa}(\rho) - \underline{\theta})p_0 b_0$, direct transfers are strictly necessary in the optimal policy.*

7 Conclusion

We analyze government interventions to support firms facing liquidity needs during a lockdown in a competitive model of financial intermediation.

Banks and firms have legacy balance sheets at the lockdown date that implies an exogenous liquidity shortfall for firms. Firms' liquidity needs can be financed by banks that are subject to risk-weighted capital requirements and funded with insured deposits. An increase in firms' overall debt aggravates moral hazard problems and reduces the profitability of their projects. The increase in project risk also creates losses for the banks in their existing portfolio of loans, reducing the risk-weighted value of their assets and limiting their capability to provide cheap new financing to the firms. This in turn further aggravates entrepreneurs' moral hazard, so that the model exhibits an amplification channel of expected output losses that operates through the balance sheet linkages between firms and banks.

The government can support firms directly through transfers or indirectly through guarantees to new bank loans or reductions in the capital requirement. Support policies aim

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at minimizing the increase in firms' debt burden associated with satisfying liquidity needs during the lockdown. Direct transfers to firms do so by reducing the funds firms must raise from banks. Indirect policies in turn imply contingent government injections of funds that augment the banks' capability to issue deposits, and, due to competition, lead to cheaper bank financing of the residual liquidity needs.

We characterize the optimal combination of these policies depending on the government's budget and the size of the liquidity shock. First, we show that a very low cost intervention might give rise to "zombie firms" and be worse than not intervening at all. That is the case when the intervention leads firms to exit the lockdown very highly indebted. Even though firms' continuation would be efficient at their pre-lockdown level of indebtedness, a government that cannot afford the cost of sufficient support would find optimal not to intervene at all and let firms be liquidated.

Second, we show that there exists a pecking order on the government policies that maximize output as a function of their expected cost. When the government budget is low, the optimal policy prescribes the exclusive use of reductions in capital requirements. By design this policy allows banks to supply cheaper liquidity to firms, while it leads to government disbursements only conditional on bad aggregate shocks. Transfers, which are uncontingent, and loan guarantees, which are contingent on idiosyncratic firms' risks, lead to some disbursements in good aggregate shocks, which do not help banks in raising deposits nor in providing cheaper financing to firms, while they increase bank rents.

The optimality of the loosening of the capital requirement relies on banks fully transmitting their increased capacity to raised deposits as cheaper financing to firms. Since banks rents are reduced as the supply of liquidity increases, there is an upper limit on how much support the government can give to firms through reductions in capital requirements, since at some point banks would not find optimal to further increase their leverage. Thus, a government with a medium budget will need to combine loosening of capital requirements with other policies. We show that transfers and loan guarantees are perfect substitutes in the optimal policy intervention mix in this government budget region. Our final result is that, when the government budget is large enough, then a strictly positive direct transfer to firms is a necessary measure in an optimal intervention.

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Contagion and conflict: Evidence from India[1]

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The health, economic and security impacts of the Covid-19 pandemic are playing out in volatile and potentially catastrophic ways, especially in conflict-affected states. The disease arrived in India during a period of heightened public protests, riots and religious polarization. In this paper, I document early evidence of the causal impact of Covid-19 proliferation on conflict risks across Indian districts. I use text-mining of conflict event descriptions to define two new measures of religious and pandemic-related conflict in addition to the standard measures of real-time conflict events provided by The Armed Conflict Location & Event Data Project (ACLED). Event study analysis indicates a sustained decline in conflict after the first Covid-19 case is reported, driven by a decrease in religious conflict and public protests. However, I also document a countervailing increase in the probability of Covid-19 related conflict. Poor districts and districts with low health infrastructure in particular demonstrate an increase in riots. These real-time findings are of first-order importance for policymakers and public administrators straddling a narrowing stringency corridor between maintaining public health and tolerance of containment policies.

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1 Thanks to seminar participants at the Graduate Institute's online development economics seminar for comments and suggestions. This research is made possible by detailed and real-time data from the Covid19India.org project (https://api.covid19india.org/) and The Armed Conflict Location and Event Data Project (ACLED). The final database, Stata and R files used for this analysis can be shared with academic reviewers and journalists upon request.

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1 Introduction

Natural disasters and their economic impacts can exacerbate underlying social tensions and increase violent conflict risks, especially in already polarized or fragmented societies (Bergholt and Lujala, 2012; Schleussner et al., 2016; De Juan et al., 2020). The health, economic and security impacts of the ongoing Covid-19 pandemic are similarly playing out in volatile and potentially catastrophic ways. The pandemic has *a priori* ambiguous impacts on conflict. First, the robust implementation of lockdowns and mobility restrictions implemented by state security services to contain viral transmission should reduce the incidence of violent events (Berman et al., 2020). However, there is also emerging evidence of a countervailing public backlash as the pandemic and containment measures impose asymmetric costs on different segments of society. This can contribute to further state-led violence to suppress public backlash.[1] Other theoretical considerations linking pandemics to conflict include the impact of resulting economic downturns on reducing individual opportunity costs of engaging in violence and limiting state capacity for counter-insurgency operations (Becker, 2000; Grossman, 1991; Dal Bó and Dal Bó, 2011; Fearon and Laitin, 2003). Evidence on which of these countervailing effects will dominate over the short to medium-term is a first order concern for public administrators and policymakers, especially in conflict-affected states with limited fiscal space to insulate their populations from the pandemic's economic shocks. As the contagion continues to proliferate, developing countries are facing a narrowing stringency possibility corridor between the health imperative to flatten the infection curve and the tolerance imperative to maintain law and order (Baldwin, 2020).

In this paper, I present early evidence of the causal impact of Covid-19 contagion on the probability of conflict across Indian districts. An event study research design with staggered treatment adoption is used to estimate short-term effects of Covid-19 contagion up to six weeks after the first case is reported in a district. My main findings are as follows: first, there is a sustained decrease in overall conflict risk after contagion is reported in an average district. This effect is primarily driven by a decline in public protests and religious violence. Second, there is a short-term, statistically significant increase in risk of Covid-19 related violence and riots for four weeks following district-level contagion. No statistically significant differences are observed in conflict pre-trends before contagion which supports a causal interpretation of the findings.

[1]For example, see: Kazmin, A. (2020, April 14). India's lockdown extension sparks migrant worker protests. Financial Times. Link

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Finally, I explore heterogeneity across districts using nightlight intensity as a proxy for district-level wealth and medical beds per capita as a proxy for district-level health infrastructure. The results show an increase in riots in poor districts and in districts with low health infrastructure. On the other hand, districts with higher health infrastructure experience a decline in conflict.

The Covid-19 pandemic arrived in India in end-January 2020 during a period of elevated civilian protests and religious polarization. India accounted for approximately 60% of all conflict events recorded in South Asia between January - April 2020 predominantly involving protests and riots (more then 4,500 events reported), according to The Armed Conflict Location and Event Data Project (ACLED). This violence was driven by the policy proposals of the Hindu-nationalist central government of the Bhartiya Janata Party (BJP). Specifically, an amendment to Indian citizenship law (Citizenship Amendment Act, 2019) was passed in early-December 2019 allowing for religious criteria to grant citizenship to refugees from neighboring countries. Another proposed legislation aimed to establish a National Registry of Citizens based on verification of Indian residents' ancestral ties to the country. Combined, these measures ignited nation-wide protests driven by fears of religious persecution of minorities. The protests and riots were met with a strong response by state security forces. As a result of this action, India witnessed a steady decline in conflict from its peak in December 2019. This decline accelerated further with the arrival of the Covid-19 pandemic in end-January. However, this trend reversed again in early-April 2020, primarily driven by an increase in conflict events related to lockdown and quarantine zones imposed to contain Covid-19. The resulting economic crisis has in turn led to an internal migrant crisis whereby newly unemployed labour from locked down urban and industrial districts are aiming to return to their places of origin in violation of lockdown rules.[2] Moreover, there is evidence of renewed increase in religious polarization and discrimination against minorities who are accused of spreading the disease.[3]

Violent conflict is a major risk for public administration and medical workers aiming to safeguard local populations from the ongoing pandemic. This paper enters the broader discussion on the security implications of the ongoing global pandemic by providing novel, micro-evidence on the impact of Covid-19 contagion on conflict risks across Indian districts. Overall, the evidence pre-

[2]For example, see: Singh, J., & Kazmin, A. (2020, April 30). India: The millions of working poor exposed by pandemic. https://on.ft.com/2VMG8Vi

[3]For example, see: Agrawal, R. (2020, April 7). Islamophobia Is Making the Coronavirus Crisis Worse. Foreign Policy. Link

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sented indicates the need for continued emphasis on maintaining public law and order, specifically by addressing the social and economic segments of society particularly affected by the pandemic. Low medical capacity districts require urgent attention for both health and security reasons. While these findings should be treated as preliminary and focusing on short-term effects, the longer-term security implications of the pandemic also represent an urgent concern in India. The root causes for the elevated public disturbance and conflict remain unchanged in terms of the religious and nationalist policy agenda of the central government. These have been further supplemented by new concerns regarding the economic crisis, internal migrant crisis and religious polarization resulting from the Covid-19 pandemic. As more disease, conflict and containment policy data emerges, we can expect to get more precise and generalizable analyses on the security impacts of the crisis.

2 Data and Research Design

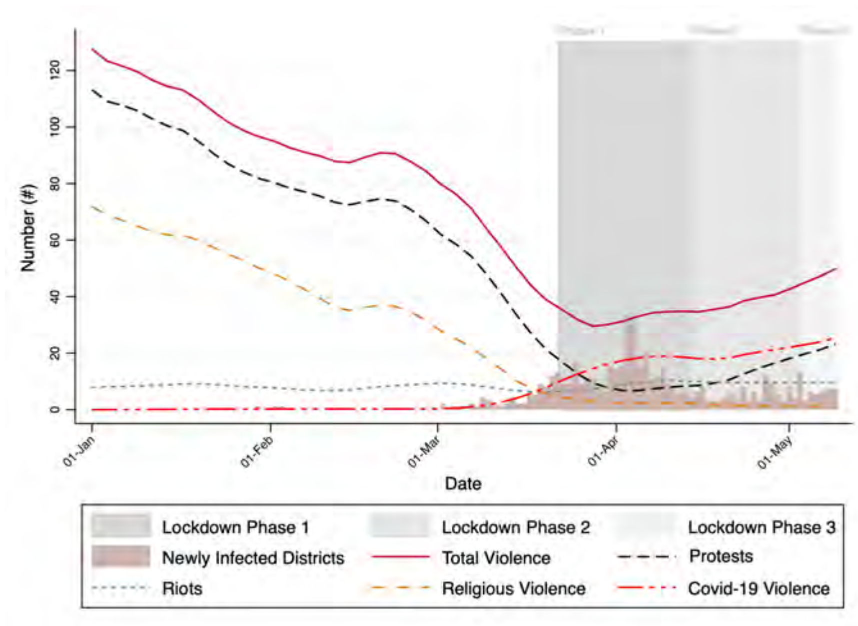

Figure 1: Contagion and Conflict in India (Jan 1 - May 9, 2020)

I use daily updated, patient-level data collected by the Covid19India project using government bulletins and official social-media announcements which is aggregated up to the district-level. Additional state-level, daily updates on the total number of Covid-19 cases, deaths and recoveries

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are also collected[4] This information is combined with geo-located data on daily conflict events provided by The Armed Conflict Location and Event Data Project (ACLED). ACLED classifies violence events further into sub-categories, including protests, riots, violence against civilians, battles, explosions and strategic events.[5]

Furthermore, two new measures for religious and pandemic-related violence are generated using text-mining of ACLED event reports that describe each recorded event.[6] My first new measure of religious violence classifies all events which include references to participants' religious affiliations, religious group affiliations, places of worship or the Citizenship Amendment Act (2019). Similarly, my measure of Covid-19 violence identifies events which refer to coronavirus, Covid-19, quarantines or lockdowns. See Figure 2 and Figure 3 for word clouds containing the most commonly occurring terms in the event descriptions for religious and Covid-19 related violence, respectively.

I combine district-level data on nightlight intensity and medical infrastructure from The Socioeconomic High-resolution Rural-Urban Geographic Platform for India (SHRUG platform) compiled by Asher et al. (2019). Nightlight intensity data comes from the U.S. Air Force's Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS). I use the latest available complete data series from 2013 and designate districts above the median as rich districts and *vice versa* for poor districts. The medical infrastructure information comes from the 2011 Population Census of India and includes the total number of beds in government clinics and hospitals. The total number of beds is divided by the population to derive a per capita measure. Districts above the median are referred to as high medical capacity districts and *vice versa* for low medical capacity districts. Finally, I collect central and state government notifications to define a lockdown indicator at the district-day level.

See Figure 1 for a graphical representation of trends in violence and Covid-19 contagion across Indian districts from January 1st until May 9th 2020. The lines represent smoothed mean values from non-parametric local polynomial regressions with bandwidth of 7 days, while the bars represent the daily total of newly infected districts. The first three phases of the Indian lockdown are represented using the shaded background. The first states and districts went into lockdown

[4]See the project website: www.covid19india.org and database: api.covid19india.org. Data availability for Covid-19 testing is not of sufficient quality to be included in this analysis.

[5]See ACLED (2019) for the complete codebook and methodology used to compile this dataset.

[6]A similar measure of Covid-19 related violence is now also available directly from ACLED. However, I prefer my novel measure for this analysis since it distinguishes between Covid-19 and religious violence in India, unlike the ACLED measure.

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Figure 2: Religious Violence

Figure 3: Covid-19 Violence

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starting from March 22nd 2020, before a nation-wide lockdown was imposed from March 25th till April 14th. This was further extended till May 3rd, followed by a third phase from May 4th till May 17th. During this third phase, districts were further divided into red, orange and green districts based on the number of reported cases.[7] Summary statistics is reported in Table 1 in the appendix.

I use a district-level event study with staggered treatment adoption (i.e., first reported Covid-19 case in a district) to estimate the dynamic, causal effects of Covid-19 contagion across Indian districts. This research design allows me to investigate the lagged impacts on my dependent variable(s) of interest, i.e. measures of total and sub-types of conflict, up to 6 weeks after contagion. To verify the identifying assumption required for a causal interpretation of the lagged effects, I can also test whether conflict events were already affected during three leading weeks before contagion. The lack of statistically significant differences in pre-treatment trends would support the identification assumption required for a causal interpretation of the treatment effects (Goodman-Bacon, 2018; Athey and Imbens, 2018). The main limitation for this methodology in this application is the potential loss of statistical power for evaluating the statistical significance of the coefficients for lagged time periods.

The estimation equation is given below:

$$\begin{aligned} Conflict_{dst} &= \alpha + \beta FirstCase_{dst} + \sum_{j=-3}^{6} \delta_j D_{ds,t_0+j} + \nu Lockdown_{dst} + \Omega \mathbf{X}_{st} + \\ &\quad \gamma District_d + \theta Date_t + \phi State_s \times Week_t + \epsilon_{dst} \end{aligned} \tag{1}$$

where $Conflict_{dst}$ represents a binary indicator equal to 1 if a conflict event is recorded in district d, state s on date t (0 otherwise). $FirstCase_{dst}$ is my treatment indicator equal to 1 on date t when the first Covid-19 is reported, while D_{ds,t_0+j} equals 1 for $-3 < j < 6$ weeks before and after $FirstCase_{dst}$. $Lockdown_{dst}$ is a vector of binary indicators equal to 1 when district d is under lockdown on date t corresponding to the three phases of the Indian lockdown.[8] X_{st} is a vector of state-level Covid-19 measures including total confirmed cases, deaths and recoveries for state s and date t. I include district and date fixed effects, $District_d$ and $Date_t$, to eliminate

[7] The fourth phase of the lockdown will last till 31 May 2020.

[8] I include the time-varying indicator for Lockdown Phase 1. The indicator for Lockdown Phase 2 is abosrbed by the date fixed effects. In the Lockdown Phase 3 (4-17 May, 2020), each district is designated as either a red, orange or green zone under lockdown. The green zone districts' indicator is treated as the base category and excluded from the regression equation.

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district-specific, time-invariant factors (e.g., transportation connections, population, population density, etc.) as well as country-wide common shocks (e.g., central government Covid-19 security and medical testing policy announcements). $State_s \times Week_t$ fixed effects are also included to control for time-varying state-level factors (e.g. regular updates in state public health policies and implementation guidelines).[9] I estimate robust standard errors ϵ_{dst} which are triple-clustered by district, date and state-week to account for serial correlation in treatment status and intra-cluster correlations in contagion by nation-date and state-week (Bertrand et al., 2004; Cameron and Miller, 2015; Abadie et al., 2017).[10] This linear probability model is estimated using ordinary least squares (OLS).

3 Results

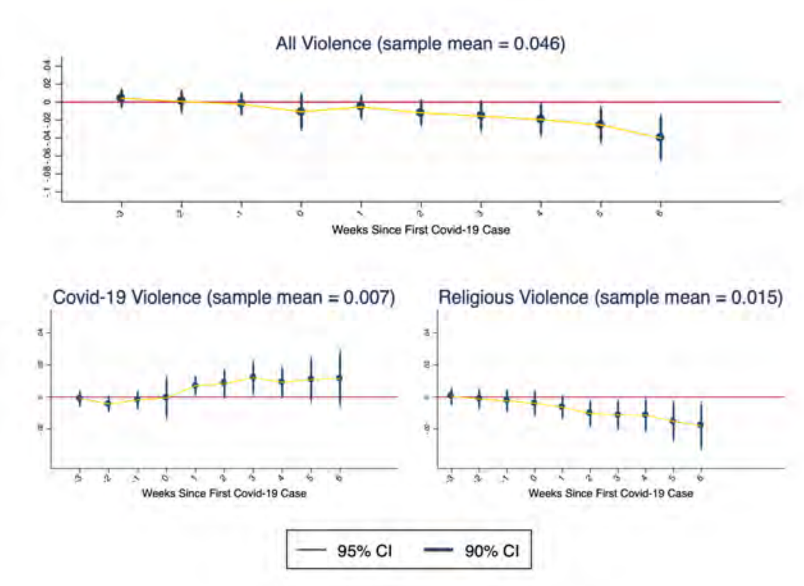

Figure 4: Results - Total Violence, Covid-19 Violence and Religious Violence

My main findings are reported in Figure 4 and Table 2 in the appendix. **First, the results indicate there is a sustained decrease in total violence risk after the first Covid-19 case**

[9]Legislation and implementation of public health policies are a prerogative of the states under the federal structure denoted by the Constitution of India.

[10]Similar research design is used in the emerging impact evaluation literature related to Covid-19 pandemic. See Brzezinski et al. (2020) and Wright et al. (2020).

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is reported in a district. The coefficients for the lead weeks are not statistically significant, while the lagged week coefficients indicate a declining trend which is statistically significant after the second week post-contagion. The estimated magnitudes indicate a 1.6 percentage point decline in week 3 (statistically significant at 90% confidence level) and increases to 4.0 percentage points by week 6 (statistically significant at 99% confidence level). The sample mean probability of violence across Indian districts of 0.046 (or 4.6%), therefore these results indicate a large and statistically significant declines in the probability of conflict.

A similar trend is observed in the event probabilities for religious violence which decline in the weeks following contagion. The results indicate a 0.6 percentage point decrease in the week following contagion (statistically significant at 90% confidence internal). The decline increases to 1.8 percentage points by the sixth lagged week (statistically significant at 95%).

There is a statistically significant increase in risk of Covid-19 related violence in the four lagged weeks following contagion. Covid-19 violence risk increases by 0.7 percentage point in the first lagged week which remains statistically significant till the fourth lagged week. The sample mean probability for Covid-19 related violence is 0.7% which indicates a 100% increase in violence related to Covid-19 disease, quarantines and lockdown.

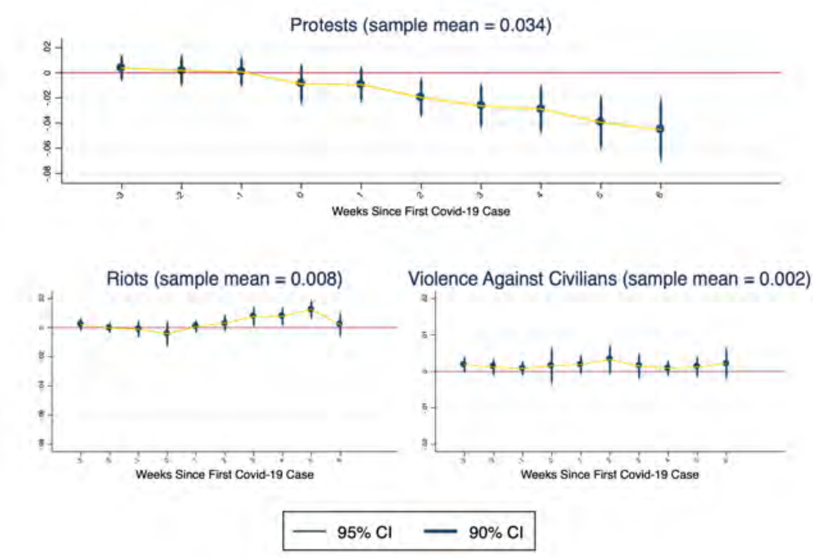

Figure 5: Results - Sub-types of Violence

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Finally, I report the results for disaggregated sub-types of conflict events in Figure 5 and Table 5 in the appendix. These findings indicate that the decline in total violence is driven predominantly by a large and statistically significant decline in the probability of public protests equal to 2 percentage points in the second lagged week which increases to 4.5 percentage point decline by lagged week 6 (statistically significant at 90%). However, I also find a statistically significant, countervailing increase in event probabilities for riots by 0.7 - 1.3 percentage points between lagged weeks three and five.

3.1 Sub-sample Results

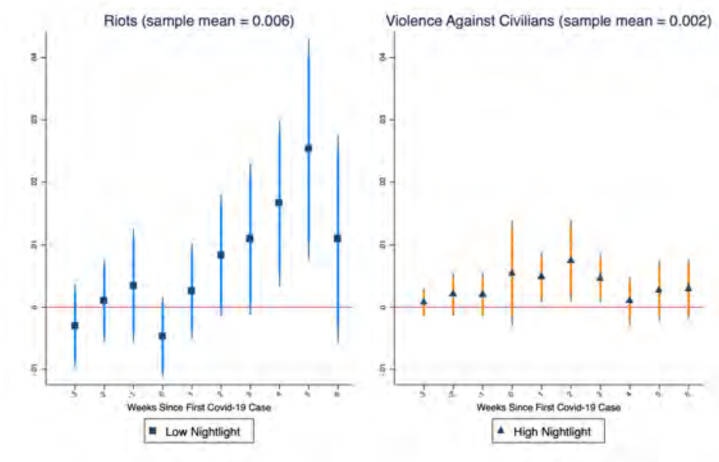

Figure 6: Results - High and Low Nighlight Districts

I conduct sub-sample analysis to explore whether district-level characteristics are associated with any diverging trends in violence. First, I test the hypothesis that district-level wealth predicts post-contagion violence due to the asymmetric economic costs imposed by the Covid-19 pandemic and associated restrictions on non-essential public movement. Nightlight intensity is used as a proxy for wealth and districts below the national median level are referred to as poor districts, while those above the median are designated as rich districts. The results are reported in Figure 6 and Table 5 in the appendix. The estimated coefficients for poor districts indicate an increase in riots in poor districts (up to 2.5 percentage points in lagged week 5, statistically significant at 99% confidence level). On the other hand, there is a short-term increase in violence against civilians in

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rich districts. This increase is indicative of security forces' actions against internal migrants who aim to return to their places of origin after losing their employment in rich districts.

Finally, I explore whether district-level medical infrastructure capacity predicts post-contagion violence as a result of public panic and backlash against poor state infrastructure. I construct a measure of high capacity districts as those with total hospital and clinic beds above median and vice versa for low capacity districts. The results are reported in Figure 7 and Table 4 in the appendix. I find that total violence declines from the second lagged week onward in high health capacity districts. In low capacity districts, on the other hand, there is a delayed and short-term increase in probability of riots (up to 3.4 percentage points in lagged week 5 which corresponds to an approximately 380% increase above the sample mean).

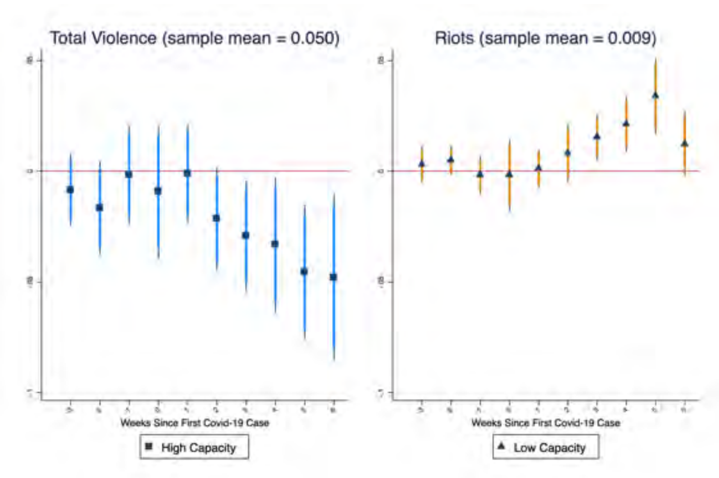

Figure 7: Results - High and Low Medical Capacity Districts

4 Conclusion

This paper provides early and real-time evidence of the impact of Covid-19 pandemic on conflict across Indian districts. Using detailed micro-data aggregated up to the district level, I use an event study design to identify the causal impacts of Covid-19 contagion on the probability of overall conflict, as well as disaggregated measures for civilians protests, riots and violence against civilians. Two novel measures of Covid-19 related violence and religious violence are also generated

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to distinguish between different trends in conflict. The results align with emerging cross-country evidence on the dampening effects of the pandemic and associated lockdowns on overall conflict (Berman et al., 2020). Moreover, this paper also provides new evidence on an increase in Covid-19 related conflict which is especially concentrated in poor and low-health capacity regions.

In conclusion, these findings should be treated as early evidence of short-term impacts of the pandemic on conflict based on preliminary data from an ongoing phenomenon. As more data emerges and the Covid-19 contagion spreads further across India, the estimations will get more precise and the findings more generalizable. However, the security implications of the pandemic indeed represent an urgent concern for India where the security impacts from the resulting economic crisis, internal migrant crisis and religious polarization have yet to manifest.

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Appendix: Tables

Table 1: Summary Statistics

	Obs.	Mean	S.D.	Min	Max
Covid19India Data					
Reported Covid-19 Cases (district, #)	93,210	0.35	5.12	0	402
Lockdown Phase 1 (binary indicator)	93,210	0.33	0.47	0	1
Lockdown Phase 2 (binary indicator)	93,210	0.15	0.35	0	1
Lockdown Phase 3: Red Zone (binary indicator)	93,210	0.007	0.086	0	1
Lockdown Phase 3: Orange Zone (binary indicator)	93,210	0.017	0.129	0	1
Lockdown Phase 3: Green Zone (binary indicator)	93,210	0.022	0.147	0	1
Daily Total Reported Covid-19 Cases (state, #)	93,210	219.501	668.401	0	6,696
Daily Total Cured Covid-19 Cases (state, #)	93,210	60.447	250.457	0	3,470
Daily Total Covid-19 Deaths (state, #)	93,210	9.863	49.299	0	731
ACLED Violence Data					
Total Violence (district, #)	93,210	0.10	1.08	0	121
Protests (district, #)	93,210	0.07	0.92	0	121
Covid-19 Violence (district, #)	93,210	0.01	0.20	0	36
Religious Violence (district, #)	93,210	0.04	0.80	0	121
Battles (district, #)	93,210	0.01	0.45	0	72
Explosions (district, #)	93,210	0.001	0.053	0	12
Riots (district, #)	93,210	0.01	0.18	0	16
Strategic Violence (district, #)	93,210	0.001	0.044	0	4
Violence Against Civilians (district, #)	93,210	0.003	0.091	0	15
Total Violence (Binary indicator)	93,210	0.05	0.21	0	1
Protests (binary indicator)	93,210	0.03	0.18	0	1
Covid-19 Violence (binary indicator)	93,210	0.01	0.09	0	1
Religious Violence (binary indicator)	93,210	0.02	0.12	0	1
Battles (binary indicator)	93,210	0.003	0.051	0	1
Explosion (binary indicator)	93,210	0.0005	0.0220	0	1
Riots (binary indicator)	93,210	0.008	0.088	0	1
Strategic Violence (binary indicator)	93,210	0.001	0.031	0	1
Violence again civilians (binary indicator)	93,210	0.002	0.047	0	1
District Characteristics					
High Medical Capacity (binary indicator)	93,210	0.618	0.486	0	1
High Nightlight Intensity (binary indicator)	93,210	0.566	0.496	0	1

Notes: Data sources are as follows - Covid-19 data is acquired from Covid19india.org (https://api.covid19india.org/), Violence data is acquired from Armed Conflict Location & Event Data Project (ACLED, acleddata.com), and finally the district and state-level characteristics are acquired from the Indian Population Census (2011). Data on majority political parties in state governments is acquired from the Election Commission of India, while the notification of Naxal-violence affected districts is acquired from the Ministry of Home Affairs, Government of India.

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Table 2: Event Study: Types of Violence

	Total Violence (1)	Covid19 Violence (2)	Religious Violence (3)
First Covid-19 Case	-0.0108	-0.0005	-0.0039
	(0.0111)	(0.0069)	(0.0043)
Lockdown Phase 1	-0.0087	-0.0034	-0.0018
	(0.0114)	(0.0046)	(0.0061)
Lockdown Phase 3 - Red zone	-0.0069	0.0354***	-0.0228***
	(0.0142)	(0.0088)	(0.0053)
Lockdown Phase 3 - Orange zone	0.0162**	0.0036	0.0065**
	(0.0071)	(0.0047)	(0.0029)
Total Covid-19 Cases	0.0000	0.0000	-0.0000
	(0.0000)	(0.0000)	(0.0000)
Cured Covid-19 Cases	-0.0000	0.0000	-0.0000**
	(0.0000)	(0.0000)	(0.0000)
Deaths from Covid-19	0.0001	-0.0000	0.0001
	(0.0002)	(0.0001)	(0.0001)
Lead Week 3	0.0041	-0.0009	0.0003
	(0.0056)	(0.0027)	(0.0029)
Lead Week 2	0.0006	-0.0043	-0.0012
	(0.0068)	(0.0026)	(0.0034)
Lead Week 1	-0.0024	-0.0019	-0.0025
	(0.0067)	(0.0031)	(0.0038)
Lag Week 1	-0.0056	0.0071**	-0.0064*
	(0.0071)	(0.0032)	(0.0038)
Lag Week 2	-0.0121	0.0084*	-0.0104**
	(0.0078)	(0.0048)	(0.0045)
Lag Week 3	-0.0158*	0.0120**	-0.0112**
	(0.0089)	(0.0055)	(0.0050)
Lag Week 4	-0.0195**	0.0092*	-0.0114**
	(0.0098)	(0.0051)	(0.0056)
Lag Week 5	-0.0256**	0.0108	-0.0152**
	(0.0109)	(0.0076)	(0.0067)
Lag Week 6	-0.0402***	0.0116	-0.0180**
	(0.0136)	(0.0094)	(0.0078)
Observations	93,210	93,210	93,210
R^2	0.16	0.06	0.13
District FEs	Yes	Yes	Yes
Time FEs	Yes	Yes	Yes
State x Week FEs	Yes	Yes	Yes

Notes: The dependent variables are binary indicators equal to 1 (0 otherwise) if any violence is reported (column 1), any Covid-19 related violence is reported (column 2), and any religious violence is reported (column 3). The treatment variable is First Covid-19 Case, which is a binary indicator equal to 1 when the first covid-19 case is reported on a particular date in a district (0 otherwise). The independent variables of interest include three lead week indicators equal to 1 in the respective weeks before First Covid-19 case, and six lag weeks indicators equal to 1 in the respective weeks following First Covid-19 Case (0 otherwise). Covariates include district-level binary indicators equal to 1 for Lockdown Phase 1 (different starting dates across districts between March 22-25 up to April 14, 2020), phase 3-red zone and phase 3-orange zone (after May 4, 2020). Lockdown Phase 2 is excluded due to lack of variation across districts and phase 3 - green zone indicator is excluded as the omitted category. Finally, state-level measures of reported Covid-19 infections, cured and deaths are included. All columns include district, date and state-week fixed effects. Robust standard errors triple-clustered by district, date and state-week are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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Table 3: Event Study: Types of Violence

	Protests (1)	Riots (2)	Violence Against Civilians (3)
First Covid-19 Case	-0.0089	-0.0043	0.0015
	(0.0083)	(0.0046)	(0.0027)
Lockdown Phase 1	-0.0113	-0.0040	-0.0023
	(0.0097)	(0.0029)	(0.0026)
Lockdown Phase 3 - Red zone	-0.0055	0.0033	-0.0010
	(0.0113)	(0.0071)	(0.0017)
Lockdown Phase 3 - Orange zone	0.0147***	-0.0039	0.0019*
	(0.0047)	(0.0031)	(0.0011)
Total Covid-19 Cases	0.0000	-0.0000	-0.0000
	(0.0000)	(0.0000)	(0.0000)
Cured Covid-19 Cases	-0.0000	-0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)
Deaths from Covid-19	0.0001	0.0001*	-0.0000
	(0.0002)	(0.0000)	(0.0000)
Lead Week 3	0.0039	0.0021	0.0018
	(0.0053)	(0.0023)	(0.0011)
Lead Week 2	0.0018	-0.0003	0.0012
	(0.0065)	(0.0018)	(0.0012)
Lead Week 1	0.0007	-0.0011	0.0008
	(0.0062)	(0.0029)	(0.0010)
Lag Week 1	-0.0093	0.0006	0.0019
	(0.0073)	(0.0022)	(0.0014)
Lag Week 2	-0.0196**	0.0031	0.0032
	(0.0081)	(0.0029)	(0.0021)
Lag Week 3	-0.0263***	0.0076**	0.0014
	(0.0091)	(0.0036)	(0.0019)
Lag Week 4	-0.0289***	0.0078**	0.0009
	(0.0099)	(0.0033)	(0.0011)
Lag Week 5	-0.0394***	0.0125***	0.0012
	(0.0112)	(0.0034)	(0.0015)
Lag Week 6	-0.0453***	0.0020	0.0022
	(0.0130)	(0.0043)	(0.0023)
Observations	93,210	93,210	93,210
R^2	0.17	0.03	0.02
District FEs	Yes	Yes	Yes
Time FEs	Yes	Yes	Yes
State x Week FEs	Yes	Yes	Yes

Notes: The dependent variables are binary indicators equal to 1 (0 otherwise) if any protests are reported (column 1), any riots are reported (column 2), and any violence against civilians is reported (column 3). Independent variables are described in Table 2. All columns include district, date and state-week fixed effects. Robust standard errors triple-clustered by district, date and state-week are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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Table 4: High vs Low Medical Capacity Districts

	Total Violence		Riots	
	Low Capacity	High Capacity	Low Capacity	High Capacity
	(1)	(2)	(3)	(4)
First Covid-19 Case	-0.0288**	-0.0093	-0.0017	-0.0065
	(0.0135)	(0.0151)	(0.0082)	(0.0046)
Lockdown Phase 1	-0.0156	-0.0005	0.0002	-0.0041
	(0.0157)	(0.0117)	(0.0059)	(0.0026)
Lockdown Phase 3 - Red zone	-0.0135	0.0307*	-0.0145	0.0165
	(0.0200)	(0.0164)	(0.0138)	(0.0110)
Lockdown Phase 3 - Orange zone	0.0056	0.0309***	-0.0033	0.0028
	(0.0113)	(0.0106)	(0.0089)	(0.0049)
Total Covid-19 Cases (state)	-0.0000	-0.0000	-0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Cured Covid-19 Cases	0.0000	0.0000	0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Deaths from Covid-19	0.0001	0.0001	0.0001	0.0000
	(0.0002)	(0.0002)	(0.0001)	(0.0001)
Lead Week 3	-0.0067	-0.0085	0.0030	0.0009
	(0.0092)	(0.0083)	(0.0043)	(0.0038)
Lead Week 2	0.0001	-0.0166	0.0048	-0.0046
	(0.0094)	(0.0107)	(0.0034)	(0.0029)
Lead Week 1	-0.0235***	-0.0018	-0.0018	-0.0016
	(0.0087)	(0.0113)	(0.0043)	(0.0053)
Lag Week 1	-0.0178*	-0.0012	0.0010	0.0009
	(0.0100)	(0.0113)	(0.0045)	(0.0035)
Lag Week 2	-0.0207*	-0.0217*	0.0080	0.0007
	(0.0119)	(0.0117)	(0.0067)	(0.0042)
Lag Week 3	-0.0157	-0.0292**	0.0154***	0.0082
	(0.0134)	(0.0126)	(0.0053)	(0.0062)
Lag Week 4	-0.0147	-0.0332**	0.0213***	0.0090*
	(0.0134)	(0.0154)	(0.0063)	(0.0049)
Lag Week 5	-0.0078	-0.0455***	0.0340***	0.0116
	(0.0176)	(0.0153)	(0.0088)	(0.0072)
Lag Week 6	-0.0210	-0.0479**	0.0123	-0.0055
	(0.0197)	(0.0190)	(0.0074)	(0.0069)
Observations	35,620	57,590	35,620	57,590
R^2	0.20	0.29	0.14	0.14
District FEs	Yes	Yes	Yes	Yes
Time FEs	Yes	Yes	Yes	Yes
State x Week FEs	Yes	Yes	Yes	Yes

Notes: The dependent variables are binary indicators equal to 1 (0 otherwise) if any violence is reported (columns 1 and 2) and any riots are reported (columns 3 and 4). Independent variables are described in Table 2. All columns include district, date and state-week fixed effects. Robust standard errors triple-clustered by district, date and state-week are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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Table 5: High vs Low Nightlight Districts

	Violence Against Civilians		Riots	
	Low Nightlight	High Nightlight	Low Nightlight	High Nightlight
	(1)	(2)	(3)	(4)
First Covid-19 Case	-0.0048**	0.0054	-0.0047	-0.0050
	(0.0023)	(0.0042)	(0.0033)	(0.0072)
Lockdown Phase 1	-0.0077	0.0020	-0.0057*	0.0036
	(0.0071)	(0.0022)	(0.0033)	(0.0045)
Lockdown Phase 3 - Red zone	-0.0001	0.0048	-0.0179*	0.0092
	(0.0027)	(0.0037)	(0.0096)	(0.0086)
Lockdown Phase 3 - Orange zone	0.0007	0.0070**	-0.0060	0.0036
	(0.0023)	(0.0033)	(0.0061)	(0.0038)
Total Covid-19 Cases	0.0000	0.0000	0.0000	-0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Cured Covid-19 Cases	0.0000	0.0000***	-0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Deaths from Covid-19	-0.0001	-0.0000***	0.0001	0.0001
	(0.0001)	(0.0000)	(0.0001)	(0.0001)
Lead Week 3	0.0003	0.0007	-0.0030	0.0035
	(0.0026)	(0.0012)	(0.0034)	(0.0036)
Lead Week 2	0.0010	0.0020	0.0010	-0.0009
	(0.0028)	(0.0017)	(0.0033)	(0.0028)
Lead Week 1	-0.0028	0.0020	0.0034	-0.0043
	(0.0022)	(0.0018)	(0.0046)	(0.0043)
Lag Week 1	-0.0011	0.0048**	0.0025	-0.0025
	(0.0024)	(0.0020)	(0.0039)	(0.0046)
Lag Week 2	0.0024	0.0074**	0.0082*	-0.0012
	(0.0045)	(0.0033)	(0.0050)	(0.0056)
Lag Week 3	-0.0005	0.0046**	0.0109*	0.0085
	(0.0034)	(0.0020)	(0.0061)	(0.0057)
Lag Week 4	-0.0008	0.0009	0.0166**	0.0095*
	(0.0023)	(0.0020)	(0.0067)	(0.0050)
Lag Week 5	-0.0061	0.0026	0.0253***	0.0141*
	(0.0038)	(0.0025)	(0.0089)	(0.0071)
Lag Week 6	0.0013	0.0029	0.0109	-0.0029
	(0.0031)	(0.0024)	(0.0084)	(0.0063)
Observations	40,430	52,780	40,430	52,780
R^2	0.13	0.13	0.15	0.13
District FEs	Yes	Yes	Yes	Yes
Time FEs	Yes	Yes	Yes	Yes
State x Week FEs	Yes	Yes	Yes	Yes

Notes: The dependent variables are binary indicators equal to 1 (0 otherwise) if any violence against civilians is reported (columns 1 and 2) and any riots are reported (columns 3 and 4). Independent variables are described in Table 2. All columns include district, date and state-week fixed effects. Robust standard errors triple-clustered by district, date and state-week are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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Aggregate demand and aggregate supply effects of Covid-19: A real-time analysis[1]

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We extract aggregate demand and supply shocks for the US economy from real-time survey data on inflation and real GDP growth using a novel identification scheme. Our approach exploits non-Gaussian features of macroeconomic forecast revisions and imposes minimal theoretical assumptions. After verifying that our results for US post-war business cycle fluctuations are largely in line with the prevailing consensus, we proceed to study output and price fluctuations during COVID-19. We attribute two thirds of the decline in 2020:Q1 GDP to a negative shock to aggregate demand. In contrast, regarding the staggeringly large decline in GDP in 2020:Q2, we estimate two thirds of this shock was due to a reduction in aggregate supply. Statistical analysis suggests a slow recovery due to persistent effects of the supply shock, but surveys suggest a somewhat faster rebound with a recovery in aggregate supply leading the way.

1 All errors are the sole responsibility of the authors. The views expressed in this document do not necessarily reflect those of the Board of Governors of the Federal Reserve System, or its staff.
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Aggregate Demand and Aggregate Supply Effects of COVID-19: A Real-time Analysis

1 Introduction

Distinguishing supply shocks from demand shocks has long been a goal of empirical macroeconomics (e.g., Shapiro and Watson, 1988, Blanchard and Quah, 1989, or Gali, 1992), in part because the appropriate monetary and fiscal policy responses may be quite different for adverse demand versus supply shocks. We define aggregate supply shocks as shocks that move inflation and real activity in the opposite direction. Similarly, demand shocks are defined as innovations that move inflation and real activity in the same direction. This definition is motivated by Blanchard (1989), who finds empirically that the joint behavior of output, unemployment, prices, wages and nominal money in the U.S. is consistent with this structure.

The decomposition is of particular interest in the context of the COVID-19 pandemic. While it is intuitively clear that, for instance, oil crises in the 1970s constituted aggregate supply shocks and the Volcker experiment an aggregate demand shock, the economic fluctuations during COVID-19 combine a range of different effects. The massive lockdown of the economy represents a large negative demand shock. However, an accompanying increase in unemployment benefits has increased the income of some low- and middle-income households at least temporarily[1], which could helpfully support aggregate demand. At the same time, supply chains in a number of industries have been affected not only internationally, with international trade in general greatly reduced, but also domestically, resulting in price increases for many goods and services.[2] With increased unemployment benefits some workers may experience greater income staying at home

[1]For instance, *"Coronavirus Relief Often Pays Workers More Than Work"*, Wall Street Journal, April 28, 2020, by Eric Morath: `http://www.wsj.com/articles/coronavirus-relief-often-pays-workers-more-than-work-11588066200`

[2]Among others, *"Grocers Hunt for Meat as Coronavirus Hobbles Beef and Pork Plants"*, Wall Street Journal, April 23, 2020, by Jacob Bunge, Sarah Nassauer, and Jaewon Kang: `http://www.wsj.com/articles/grocers-hunt-meat-as-coronavirus-hobbles-beef-and-pork-plants-11587679833`.

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rather than returning to work.[3] This situation may have positive effects on public health by supporting social distancing, but it may also further complicate the process of business re-openings. Among others, Mulligan (2012) argues that this type of unemployment benefits has been one of the main reasons for the long and slow recovery following the Great Recession. Low energy prices could potentially offset some of the negative supply effects: oil prices have plummeted due to a combination of OPEC policies and weak fuel demand.[4]

In this article, we quantify the relative magnitudes of the aggregate demand and aggregate supply shocks during the first two quarters of COVID-19. Our identification of demand and supply shocks follows Bekaert, Engstrom, and Ermolov (2020) and differs from the extant literature. First, we extract aggregate supply and demand shocks for the US economy from survey data on inflation and real GDP growth. By using survey-based forecast revisions to measure shocks, there is no need to model the conditional means of inflation and output growth, and survey-based shocks are observed in real time. Second, we use a novel approach to resolve the identification problem for the structural aggregate supply and aggregate demand (AS/AD) shocks. We exploit unconditional higher-order moments in the data, which we show to be highly statistically significant in the postwar US data, even excluding the COVID-19 episode. Despite this economically agnostic approach, we show that the structural shocks that we identify exhibit some intuitive properties. For example, in a classic paper, Blanchard and Quah (1989) use a vector-autoregressive dynamic structure to identify "demand-like" shocks as shocks that affect output temporarily, whereas supply disturbances have a permanent effect on output. The shocks that we estimate also exhibit these dynamic properties, even though we do not impose them ex-ante.

We first examine the AS/AD classification of earlier recessions, finding that our clas-

[3]For example, *Paying Americans Not to Work*, Wall Street Journal, April 22, 2020, Editorial: http://www.wsj.com/articles/paying-americans-not-to-work-11587597150.

[4]For example, *Oil Prices Fall as Demand Concerns Outweigh Supply Cuts*, Wall Street Journal, May 11, 2020, by Amrith Ramkumar: https://www.wsj.com/articles/oil-prices-swing-after-saudi-arabia-deepens-supply-cuts-11589205635,

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sification of the recessions up to the eighties largely corroborates earlier work by Gali (1992). We find that negative demand shocks contributed more importantly to the Great Recession than supply shocks, in line with work by Mian and Sufi (2014), who conclude using micro data that lower aggregate demand was the main cause of the steep drop in employment during the Great Recession.

We next proceed to quantify the AS/AD decomposition of the COVID-19 event. We estimate that the real GDP growth shock during 2020:Q1 is -6.6 percent at an annual rate, and is largely due to an aggregate demand shock. In 2020:Q2 the real GDP growth shock is -34.3 percent at an annual rate. We find that roughly two thirds of it, -19.5 percent, is due to an aggregate supply shock and the rest, -14.8 percent, is due to an aggregate demand shock. Forecast revisions for 2020:Q3-2021:Q1 suggest that the recovery will be "check mark"-shaped and more aggregate supply driven, although the aggregate demand component contributes to the recovery as well. This somewhat contradicts a statistical analysis based on historical data which suggests a multi-year recovery, because of the permanent growth effect due to the large AS shock, a view some leading experts concur with.[5]

The rest of the paper is organized as follows. Section 2 describes our structural framework and identification. Section 3 focuses on the estimation and Section 4 on the COVID-19 analysis. Section 5 concludes.

2 Modeling Macro Shocks

2.1 A simple model of aggregate supply and demand shocks

Consider a bivariate system in real GDP Growth (g_t) and inflation (π_t):

$$\begin{aligned} g_t &= E_{t-1}[g_t] + u_t^g, \\ \pi_t &= E_{t-1}[\pi_t] + u_t^\pi, \end{aligned} \tag{1}$$

[5]For example, "Why Our Economy May Be Headed for a Decade of Depression", New York Magazine, May 22, by Eric Levitz: http://nymag.com/intelligencer/2020/05/why-the-economy-is-headed-for-a-post-coronavirus-depression-nouriel-roubini.html.

where E_{t-1} denotes the conditional expectation operator. We model the shocks to output growth and inflation as a function of two structural shocks, u_t^s and u_t^d:

$$\begin{aligned}
&u_t^\pi = -\sigma_{\pi s} u_t^s + \sigma_{\pi d} u_t^d, \\
&u_t^g = \sigma_{gs} u_t^s + \sigma_{gd} u_t^d, \\
&\sigma_{\pi s} > 0, \sigma_{\pi d} > 0, \sigma_{gs} > 0, \sigma_{gd} > 0, \\
&Cov(u_t^d, u_t^s) = 0, Var(u_t^d) = Var(u_t^s) = 1.
\end{aligned} \tag{2}$$

The first fundamental economic shock, u_t^s, is an aggregate supply shock, defined so that it moves GDP growth and inflation in opposite directions, as happens, for instance, in episodes of stagflation. The second fundamental shock, u_t^d , is an aggregate demand shock, defined so that it moves GDP growth and inflation in the same direction as would be the case in a typical economic boom or recession. Supply and demand shocks are assumed to be uncorrelated, and we also assume co-skewness moments to be zero ($E[(u_t^s)^2 u_t^d] = E[u_t^s (u_t^d)^2] = 0$).

Note that the sample covariance matrix of the shocks from the bivariate system in (1) only yields three unique moments (two variances and the covariance), but we need to identify four coefficients in equation (2) to extract the supply and demand shocks. Hence, absent additional assumptions, a system with Gaussian shocks would be underidentified. Fortunately, it has been well established that macroeconomic data exhibit substantial non-Gaussian features (see, e.g., Evans and Wachtel (1993) for inflation, and Hamilton (1989) for GDP growth). Thus, we exploit that the demand and supply shocks are potentially non-Gaussian in that they may have non-zero unconditional skewness and excess kurtosis. For example, there are four available univariate unconditional skewness and co-skewness moments for GDP growth and inflation. These four moments, in conjunction with the three available second moments, could in principle be used to identify the four $\sigma_{\pi/g,s/d}$ parameters (of course, we also have to estimate the unconditional skewness and kurtosis of the supply and demand shocks in this case, which we do).

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While econometrically it is clear that non-Gaussianity achieves identification (see Lanne, Meitz, and Saikkonen, 2017, for a theoretical paper on obtaining identification through higher-order moments in a VAR and Bekaert, Engstrom, and Ermolov, 2019, for an empirical application to the US term structure), it is useful to clarify the economic sources of identification. Consider, for example, co-skewness moments, that is, in unscaled form, the expectation of the inflation shock squared times the GDP growth shock or vice versa. Under our formulation, the coskewness of inflation and real activity shocks are as follows:

$$\begin{aligned} E[u_t^g(u_t^\pi)^2] &= \sigma_{gd}\sigma_{\pi d}^2 E[(u_t^d)^3] + \sigma_{gs}\sigma_{\pi s}^2 E[(u_t^s)^3], \\ E[(u_t^g)^2 u_t^\pi] &= \sigma_{gd}^2\sigma_{\pi d} E[(u_t^d)^3] - \sigma_{gs}^2\sigma_{\pi s} E[(u_t^s)^3]. \end{aligned} \tag{3}$$

Clearly, such moments only depend on the shock sensitivities and the third moments of supply and demand shocks and, thus, would be zero under Gaussianity. Suppose that demand and supply shocks are negatively skewed to a similar degree (if they are differentially skewed, that information also helps identification). In this case, the $E[u_t^g(u_t^\pi)^2)]$-moment has a negative contribution coming from both supply shocks (as the movements of inflation and GDP growth in opposite directions are cancelled) and demand shocks. However, the $E[(u_t^g)^2 u_t^\pi]$ moment retains its negative contribution from demand shocks but obtains a positive contribution from supply shocks (as the negative skewness is multiplied by shock exposures of opposite sign). Therefore, skewed structural shocks should result in different magnitudes of these two co-skewness moments, with the inflation squared moment much more negative than the GDP growth squared moment. The exact relative magnitude of these two moments then reveals information about the sensitivity of the macro shocks to the structural shocks.

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2.2 The Interpretation of the Macro Shocks

The main advantage of the definition of the supply and demand shocks above is that it carries minimal theoretical restrictions (only a sign restriction).[6] However, these supply and demand shocks definitions do not necessarily comport with demand and supply shocks in, say, a New Keynesian framework (see e.g. Woodford, 2003) or identified VARs in the Sims tradition (Sims, 1980).[7] The classic Blanchard and Quah (1989) paper famously identifies "demand-like" shocks as those that affect output only temporarily whereas supply disturbances have a permanent effect on output, with neither having a long run effect on unemployment rate. However, Blanchard (1989) notes that these short- and long-run effects of supply and demand shocks are consistent with responses to shocks in the context of standard Keynesian models. For instance, supply shocks include productivity shocks which tend to have a longer run effect on output. We reverse the identification strategy here, by first exploiting the sign restrictions to identify the shocks, and then verifying their long-run impact on inflation and real activity in subsequent analysis.

3 Identifying Macro Shocks in the US economy

The estimation consists of two steps. First, we use survey data to measure reduced-form shocks to the macroeconomic activity. Second, we filter the demand and supply shocks from the system in equation (2) by estimating a classical minimum distance system that includes higher-order unconditional moments of the macroeconomic variables. We begin by describing the data we use.

3.1 Data

As indicated above, we use survey data to identify reduced-form macroeconomic shocks. The survey data are from the Survey of Professional Forecasters (SPF). They are

[6]The idea to impose a minimal set of sign restrictions to achieve identification is reminiscent of Uhlig's (2005) identification scheme for monetary policy shocks. Gali (1992) uses sign restrictions similar to ours in a VAR setting but does not obtain identification through non-Gaussianity.

[7]Furthermore, in some models the "supply" shocks might move real activity and inflation in the same direction: see, for instance, news shocks in Cochrane (1994).

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available quarterly from 1968:Q4. We use data through 2019:Q2 for the estimation and then analyze the dynamics during 2020:Q1 and 2020:Q2 using the estimated parameters. In this way, our analysis of the COVID-19 event is an out-of-sample exercise, relying on identification using higher-order moments that exist in the in-sample period.

We show below that even prior to the COVID-19 recession, non-Gaussian features of our macroeconomic survey data are very statistically and economically significant in our sample. To identify inflation shocks we use revisions to survey forecasts:

$$u_t^{\pi} = E_t[\pi_t] - E_{t-1}[\pi_t], \tag{4}$$

where π_t is the percentage change in the GDP deflator and E_t refers to the mean survey-based expectation at time t. The SPF survey is usually published in the middle of the second month of each quarter.[8] As a concrete example, our measured revision to inflation for the period 2020:Q1 is equal to the SPF expectation as of early February 2020 for inflation for 2020:Q1 inflation minus the expectation for 2020:Q1 inflation that was measured in the previous SPF survey, taken in early November 2019. Our inflation data refers to the percentage change in the GDP price deflator over the first (calendar) quarter of 2020; this data is first published by the Bureau of Economic Analysis in April.

Survey-based measures have the advantage of being model-free, and also capture, in principle, the real time expectations of market participants. Ang, Bekaert and Wei (2007) show that inflation expectations from the SPF provide accurate forecasts of future inflation, compared to statistical forecasts. Similarly, we measure shocks to the outlook for real activity as:

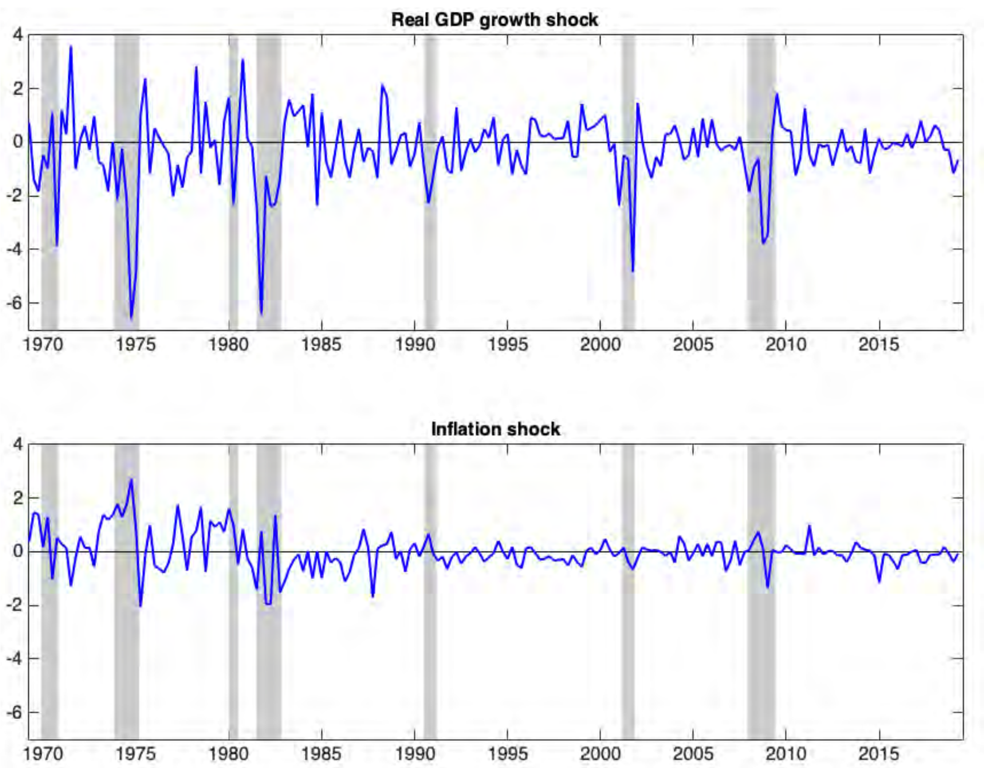
$$u_t^{g} = E_t[g_t] - E_{t-1}[g_t], \tag{5}$$

where g_t is the percentage change in real GDP growth.

[8] A few historical disruptions have caused the survey to be published later in the quarters. See `https://www.philadelphiafed.org/-/media/research-and-data/real-time-center/survey-of-professional-forecasters/spf-release-dates.txt?la=en`.

Using forecast revisions to measure shocks obviates the need to model GDP growth and inflation dynamics and conduct model selection. Figure 1 depicts the real GDP and inflation shocks that we use in the estimation, expressed at annual rates. Shocks to real GDP shocks are generally larger earlier in the sample, and deeply negative spikes occur during recessions throughout the sample. Similarly inflation variability is higher earlier in the sample and large positive and negative spikes are evident during recessions that occur early in the sample period. Later in the sample period, the overall variability of inflation decreases and the shocks during recessions are notably negative.

Figure 1 – Real GDP Growth and Inflation Shocks. The sample is quarterly 1968Q4-2019Q2. Shading corresponds to NBER Recessions.



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3.2 Identifying supply and demand shocks

To begin, note that if we can identify the σ coefficients in (2), we can infer the supply and demand shocks from the original macro shocks u_t^π and u_t^g.[9]

To estimate the σ coefficients, we use information in all available 2^{nd}, 3^{rd} and 4^{th} order unconditional moments of the reduced-form macroeconomic shocks in a classical minimum distance (CMD) estimation framework (see, e.g., Wooldridge, 2002, pp. 445-446). Specifically, we calculate 12 statistics based on the two series of shocks measured in the survey data. These are the unconditional standard deviations (2 statistics), the correlation (1 statistic), univariate (scaled) skewness and excess kurtosis (4 statistics), co-skewness (2 statistics), and co-excess kurtosis measures (3 statistics). The parameters we use to match these moments include the loadings of inflation and real activity onto supply and demand shocks (σ_π^d, σ_π^s, σ_g^d, σ_g^s), the unconditional skewness ($E[(u_t^d)^3]$ and $E[(u_t^s)^3]$) and excess kurtosis ($E[(u_t^d)^4]-3$ and $E[(u_t^s)^4]-3$) of supply and demand shocks, and the excess cross kurtosis of supply and demand shocks ($E[(u_t^d)^2(u_t^s)^2]-1$). The final parameter, $E[(u_t^d)^2(u_t^s)^2]-1$, captures that the volatility of supply and demand shocks may be correlated, even though the shocks themselves are assumed to be uncorrelated.

With 12 moments to match and 9 parameters to estimate, our system is overidentified, thus requiring a weighting matrix. To generate a weighting matrix, we use the inverse of the covariance matrix of the sampling error for the statistics, consistent with asymptotic theory suggesting that this choice leads to efficient estimates. We use a block bootstrapping routine to calculate the covariance matrix,. Specifically, we sample, with replacement, blocks of length 12 quarters of the two survey-based macroeconomic shocks, to build up a synthetic sample of length equal to that of our data. We calculate the same set of higher order statistics for each of 10,000 synthetic samples. We then calculate the covariance matrix of these statistics across bootstrap samples.

Table 1 reports the sample higher-order moments we use in the estimation, bearing

[9]The inverse of the 2×2 matrix $\begin{bmatrix}\sigma_{gs} & \sigma_{gd}\\ -\sigma_{\pi s} & \sigma_{\pi d}\end{bmatrix}$ multiplied by $\begin{bmatrix}u_t^g\\ u_t^\pi\end{bmatrix}$ yields $\begin{bmatrix}u_t^s\\ u_t^d\end{bmatrix}$.

in mind that these statistics are based on the in-sample period that ends in 2019:Q2. Not surprisingly, all volatility statistics are statistically significantly different from zero, but the unconditional correlation of inflation revisions and revisions to real growth is insignificantly different from zero at -0.13. Real growth shocks are significantly negatively skewed with a skewness of -1.23, and the co-skewness moment involving inflation revisions squared times real growth revisions is significantly negative. Together, these two moments suggest that that real growth is, on average, more negative when inflation volatility is high and when real growth volatility is high. The excess kurtosis of real growth is significantly positive with a value of 4.71, as is the fourth moment involving squared inflation revisions times squared growth revisions. The latter indicates that the volatilities of inflation and real growth tend move together. The p-value for the joint significance of all the 3^{rd} and 4^{th} order moments is 0.26 percent, strongly rejecting the hypothesis that the data are distributed unconditionally according to a multivariate Gaussian distribution and providing strong support for our identification assumption.

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Table 1 – Unconditional Moments of Macroeconomic Revisions: Classical Minimum Distance Fit. The sample is quarterly 1968Q4-2019Q2. *** corresponds to statistical significance at the 1 percent level.

	Standard deviation		Correlation		
	u_t^π	u_t^g	$u_t^\pi u_t^g$		
Data	0.6361	1.1885	-0.1344		
Standard error	(0.0913)	(0.1448)	(0.1555)		
Fitted value	[0.7083]	[1.3295]	[-0.2776]		
	Skewness		Coskewness		
	u_t^π	u_t^g	$(u_t^\pi)^2 u_t^g$	$u_t^\pi (u_t^g)^2$	
Data	0.2005	-1.2343	-0.7873	0.4309	
Standard error	(0.3712)	(0.3890)	(0.2674)	(0.4884)	
Fitted value	[0.3663]	[-1.4465]	[-0.9808]	[0.4874]	
	Excess kurtosis		Excess cokurtosis		
	u_t^π	u_t^g	$(u_t^\pi)^2 (u_t^g)^2$	$(u_t^\pi)^3 u_t^g$	$u_t^\pi (u_t^g)^3$
Data	1.7280	4.7138	1.9239	-0.5464	-1.6186
Standard error	(0.9813)	(1.3877)	(0.8979)	(1.1467)	(1.5647)
Fitted value	[1.7502]	[4.3216]	[2.6462]	[-1.7761]	[-3.2401]
Test for joint significance of 3^{rd} and 4^{th} order moments					
J-stat	25.3618				
p-value	0.26%***				
Overidentification test					
J-stat	2.9781				
p-value	38.74%				

In Table 2, Panel A, we report the supply and demand loadings for GDP growth and inflation. These are generally quite precisely estimated. Our estimates suggest that supply and demand shocks contribute roughly equally to the unconditional variance of inflation shocks over this sample period: the inflation supply and demand loadings are -0.48 and 0.51, respectively. For real growth, supply shocks, unconditionally, contribute somewhat more than demand shocks to the overall variance: the real GDP growth supply and demand loadings are 1.18 and 0.60 respectively.

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Table 2 – CMD Parameter Estimates. Asymptotic standard errors are in parentheses.

Panel A: Loadings of Reduced-form Shocks onto Supply and Demand Shocks		
	u_t^π	u_t^g
u_t^s	-0.4829	1.1802
	(0.0566)	(0.1129)
u_t^d	0.5141	0.6035
	(0.0685)	(0.1064)
Panel B: Higher-order Moments of Supply and Demand Shocks		
	Skewness	Excess kurtosis
u_t^s	-1.9563	6.8535
	(0.3873)	(1.5692)
u_t^d	-0.6896	1.0062
	(0.5413)	(1.6825)
Co-excess kurtosis	-0.0095	
	(0.2843)	

Returning to Table 1, in square brackets we report the fitted values for all statistics. Recall that because the system is overidentified by 3 degrees of freedom, not all moments can be fit perfectly. Nonetheless the overall fit is quite good. All second and third-order moments are within a one standard error band of the point estimate, and all the fourth order moments are within a two standard error band. We also report a standard overidentification test for the CMD model fit. The corresponding p-value is 38.74 percent implying that the model is not rejected.

3.3 Properties of Demand and Supply Shocks

In Panel B of Table 2, we report the estimated skewness and kurtosis of the supply and demand shocks. Both shocks are negatively skewed and leptokurtic (though only for supply shocks are these estimates statistically significant). Interestingly, we find little evidence for excess co-kurtosis, meaning that the variances of supply and demand shocks do not covary strongly on an unconditional basis.

Figure 2 depicts the supply and demand shocks that we recover from this exercise. Both sets of shocks exhibit greater overall variability early in the sample period, followed by a secular decline that perhaps reflects the so-called "Great Moderation", although

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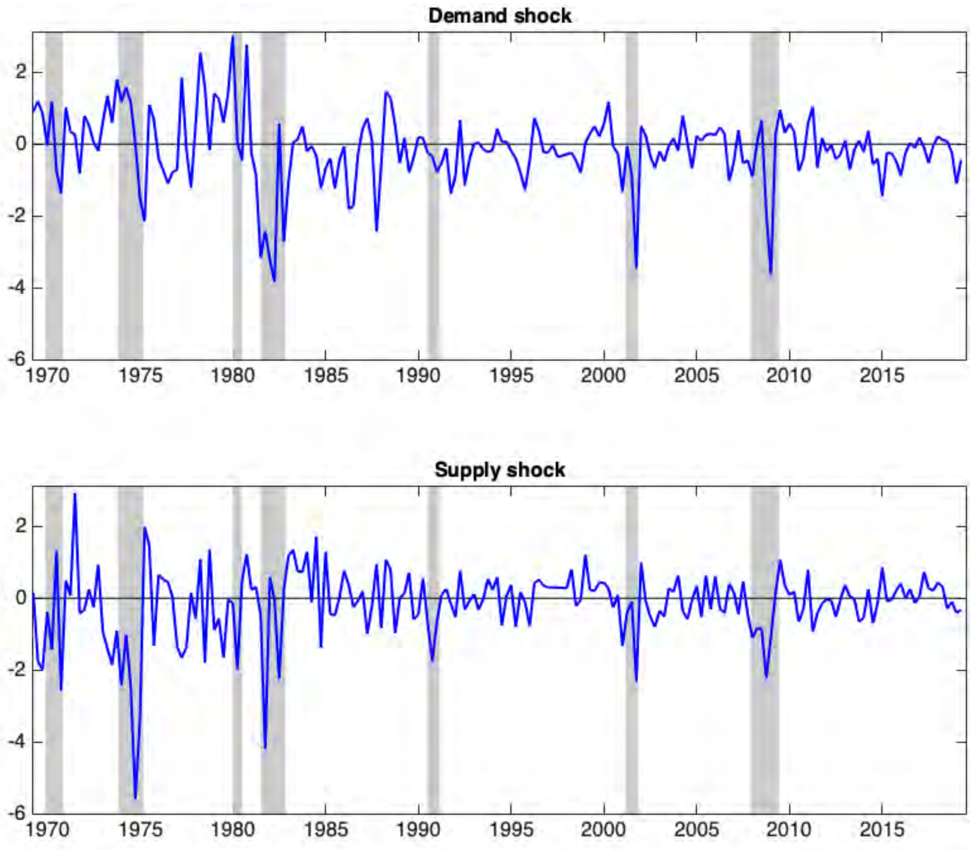
deeply negative shocks occur during recessions throughout the entire sample.

Figure 2 – Aggregate Demand and Aggregate Supply Shocks. The sample is quarterly 1968Q4-2019Q2. Shading corresponds to NBER Recessions.



Our identification of supply and demand shocks utilizes a set of minimal linear sign restrictions and information in higher order moments. These sign restrictions are present in other classic papers as well, such as Gali (1992), but are accompanied by a set of additional economic restrictions (e.g., that demand shocks have no long run effect on the level of GDP as in the classic Blanchard and Quah (1989) paper) which we do not need.[10]

[10] Shapiro and Watson (1988) show that key results may depend on assumptions regarding differencing and cointegration of the data.

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We now characterize the long run effects of the structural shocks using standard impulse response analysis.

To do so, we estimate a VAR on real GDP growth and aggregate inflation, using final, revised quarterly data from the St. Louis Federal Reserve "Fred". Our demand and supply shocks computed from forecast revisions serve as the structural shocks to the VAR and we retrieve the contemporaneous loadings of real GDP growth and inflation on these shocks by simple regression analysis. We then compute impulse responses of real GDP growth and inflation to one standard deviation demand and supply shocks, with confidence intervals determined via block-bootstrap. In particular, our VAR model is:

$$Y_t = A_0 + A_1 Y_{t-1} + S \begin{bmatrix} u_t^s \\ u_t^d \end{bmatrix} + \epsilon_t, \tag{6}$$

where Y_t is the vector of final, revised real GDP growth and inflation, $\begin{bmatrix} u_t^s \\ u_t^d \end{bmatrix}$ are pre-estimated structural shocks from the SPF, and ϵ_t is a residual noise vector.

Table 3 contains the results, with the contemporaneous (long-term) effects of demand and supply shocks on the left (right). The effects are consistent with the standard Keynesian interpretation. Demand shocks have positive short run effects on real GDP growth (with the contemporaneous response being 0.19 percent and highly statistically significant) but their cumulative effect on output is 0.00 percent out to two decimal places. Supply shocks generate larger short run GDP growth effects (0.32 percent and highly statistically significant) and their cumulative effect at 0.66 percent is economically large and strongly statistically significantly different from zero.

As expected, demand and supply shocks have very different effects on the price level. The contemporaneous demand shock increases the price level by 0.33 percent and the contemporaneous supply shock decreases it by 0.18 percent, with both values highly statistically significant. While the cumulative effect of the demand shock is 1.17 percent and statistically significant, the supply shock effect peters out to zero. In sum, our identification scheme yields shocks whose long-run effects are consistent with a well-established macroeconomic literature.

Table 3 – VAR Impulse Responses of Real GDP and Aggregate Price Level to One Standard Deviation Demand and Supply Shocks. The data are 1968:Q4-2019:Q2 quarterly. The VAR model is: $Y_t = A_0 + A_1 Y_{t-1} + S[u_t^s, u_t^d]' + \epsilon_t$, where Y_t is the vector of final, revised real GDP growth and inflation, $[u_t^s, u_t^d]'$ are pre-estimated structural shocks from the SPF, and ϵ_t is a residual noise vector. The cumulative impulse responses include the quarter 0 (where the shocks happened) responses. Numbers in parentheses are probabilities that the impulse response is less than 0 obtained from 10,000 block-bootstrap samples of historical length with the block size of 8 quarters. The asterisks, ***, correspond to statistical significance at the 1 percent level.

	Contemporaneous (quarter 0) responses		Cumulative (20 quarters) responses	
Shock	Real GDP level	Price level	Real GDP level	Price level
Demand	0.19%***	0.33%***	0.00%	1.17%***
	(0.22%)	(0.00%)	(52.25%)	(0.00%)
Supply	0.32%***	-0.18%***	0.66%***	-0.45%
	(0.00%)	(99.98%)	(0.00%)	(93.95%)

3.4 Characterizing NBER Recessions Using Aggregate Demand and Supply Shocks

Our identification of supply and demand shocks allows us to characterize recessions as either supply or demand driven (or a combination of both). Table 4 quantifies this by simply adding up the (net) demand and supply shocks over the recession period (that is, positive and negative shocks can cancel each other out). The 1980 recession did not feature negative cumulative demand shocks but all the other recessions did, with the 1981-82 recession and the Great Recession featuring the largest negative demand shocks. All recessions except the 1981-1982 one featured negative supply shocks, with the largest negative shocks occurring in the 1969-1970 and 1973-1975 recessions. On a relative basis, the first three recessions were predominantly supply driven whereas three of the last four were more demand driven (the exception being the 1990-91 recession). Figure 2 visualizes this analysis.

For the first five recessions, these results are broadly consistent with Gali's (1992)

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results, who also characterizes the 1973-75 recession as mostly supply driven and the 1981-82 recession as mostly demand driven. There is a debate on the origins of the Great Recession of 2008-2009, with some researchers arguing for the predominance of a large negative aggregate demand shock (see, e.g., Mian and Sufi, 2014), others stressing the importance of supply shocks (see, e.g., Ireland, 2011, or Mulligan, 2012). We also find that negative demand shocks contributed more importantly to the Great Recession than supply shocks did.

Table 4 – Decomposition of Real GDP Growth during NBER Recessions into Demand and Supply Components. The aggregate demand component of the GDP growth is computed as σ_{gd} multiplied by the sum of aggregate demand shocks over the period of the recession. The aggregate supply component of the GDP growth is computed as σ_{gs} multiplied by the sum of aggregate supply shocks over the period of the recession.

NBER Recession	GDP shock: demand component	GDP shock: supply component
1969Q4-1970Q4	-0.34%	-2.11%
1973Q4-1975Q1	-0.08%	-2.33%
1980Q1-1980Q2	0.72%	-0.51%
1981Q3-1982Q4	-3.63%	0.12%
1990Q4-1991Q1	-0.20%	-0.32%
2001Q1-2001Q4	-1.55%	-0.37%
2008Q1-2009Q2	-1.92%	-0.18%

4 The COVID-19 Episode

4.1 The Shock

We start by analyzing 2020:Q1, the first quarter in which the COVID-19 pandemic affected U.S. economic activity. All GDP growth and inflation values below are changes from the previous quarter expressed at an annual rate. An important caveat about this analysis is that 2020:Q1 SPF was conducted in February, well before the devastating effects on the U.S. economy became apparent in the last three weeks of March. Thus, COVID 19 effects are not reflected at all in the SPF survey published in 2020:Q1. For this reason, we analyze 2020:Q1 dynamics using the actual macroeconomic data. In particular, for inflation we use the Bureau of Labor Statistics release on April 10^{th}, 2020, which indicates 2020:Q1 inflation of -0.80 percent. For real GDP growth we use the U.S. Department of Commerce release on April 29th, 2020, which estimates 2020:Q1 real GDP growth of -4.80 percent. We subtract off the survey-based expectations for these variables as measured from the previous SPF survey in November; this procedure implies a GDP growth shock of -6.60 percent and an inflation shock of -2.73 percent. These are very large negative shocks: the leftmost two columns of Table 5 indicate that the 2020:Q1 shocks were the strongest negative shocks for both real GDP growth and inflation in our sample. Both were about twice the size of the shocks seen in 2008:Q4 during the financial crisis. As shown in the middle two columns of Table 5, we estimate that the magnitude of the demand shock was -7.1 in 2020:Q1 and the aggregate supply shock was -1.9. While the demand shock in 2020:Q1 was unprecedented in magnitude, stronger supply shocks hav been observed in the sample period. The rightmost columns in Table 5 show that out of a total of -6.6 percent real GDP growth shock in 2020:Q1, we estimate that -4.3 percent is due to an aggregate demand shock and -2.3 percent is due to an aggregate supply shock. Intuitively, we find that the demand shock was more important, because real GDP growth and inflation shocks were both strongly negative. Table 5 also provides standard errors derived from standard errors of inversion coefficients (σ:s) in Table 2, which are quite tight.

We now proceed to analyze 2020:Q2, for which we can return to using our standard survey-based measure of shocks. The leftmost column of Table 5 indicates that the real GDP growth shock is an astounding 34.3 percent at an annual rate (reflecting an expected growth rate of -32.2 percent for the quarter versus an expectation of 2.1 percent from the previous survey) and the inflation shock is -4.6 percent (reflecting an expectation of -2.6 percent in the Q2 survey versus a previous expectation of 2 percent). The comparison to historical extremes in Table 5 indicates that the real GDP growth shock is truly extraordinary. While the inflation shock is also the largest in the sample, it does not stand out as much, because strong deflationary shocks have occurred before, for example, during the 1981-1983 recession. Together these translate into an estimated demand shock of -24.5 and a supply shock of -16.5, both being clearly the largest negative demand and

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supply shocks, respectively, in our sample, as can be seen in the middle columns of Table 5. Keeping in mind that both supply and demand shocks were defined to have an unconditional standard deviation of one in the in-sample period, it is clear that shocks of these magnitudes are astonishingly large. Given that a very large real GDP growth shock is accompanied by a relatively much smaller inflation shock, both aggregate demand and aggregate supply components must be large under our estimated coefficients in Table 2: both shocks will contribute negatively to real GDP growth but their effects on inflation are offsetting. This decomposition implies that out of a -34.3 percent real GDP growth shock -14.8 percent is due to aggregate demand and -19.5 percent due to aggregate supply.

4.2 The Shape of the Recovery

With the COVID shock in the first half of 2020 showing a strong aggregate supply component, a standard new-Keynesian or Blanchard-Quah (1989)-type model would suggest that the recovery could unfortunately be relatively slow and incomplete. This is because negative supply shocks are usually associated with hits to productivity growth, increases in the natural rate of employment, and other reduction in the productive capacity of the economy from which some time may be required to recover. Indeed, anecdotal reports that some business models may no longer be economically viable, for instance, in sectors such as tourism, hospitality, and entertainment, are examples suggesting that a period of difficult adjustment may lay ahead, denting the potential output of the economy. We can illustrate the expected pattern of recovery using our previously estimated VAR for Table 3. Figure 3 shows the predicted responses of GDP growth due to 2020:Q2 shock. While the demand component of the negative hit to GDP recovers fairly quickly over the next several quarters, the supply component remains deeply negative for many years.

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Table 5 – COVID-19 Shocks. Shocks are quarterly expressed at an annualized rate. The aggregate demand component of the GDP growth is computed as σ_{gd} multiplied by the sum of aggregate demand shocks over the period of the recession. The aggregate supply component of the GDP growth is computed as σ_{gs} multiplied by the sum of aggregate supply shocks over the period of the recession. CMD-implied standard errors are in parentheses.

	Real GDP growth shock	Inflation shock	Demand shock	Supply shock	Real GDP growth demand component	Real GDP growth supply component
2020:Q1	-6.6%	-2.7%	-7.1	-1.9	-4.3%	-2.3%
					(0.8%)	(0.2%)
2020:Q2	-34.3%	-4.6%	-24.5	-16.5	-14.8%	-19.5%
					(2.6%)	(1.9%)
Max(1968Q4-2019:Q2)	3.6%	2.7%	3	2.9	1.8%	3.5%
Min(1968Q4-2019:Q2)	-6.6%	-2.1%	-3.8	-5.6	-2.3%	-6.6%
2008:Q4	-3.5%	-1.4%	-3.7	-1.1	-2.2%	-1.3%
					(0.4%)	(0.1%)

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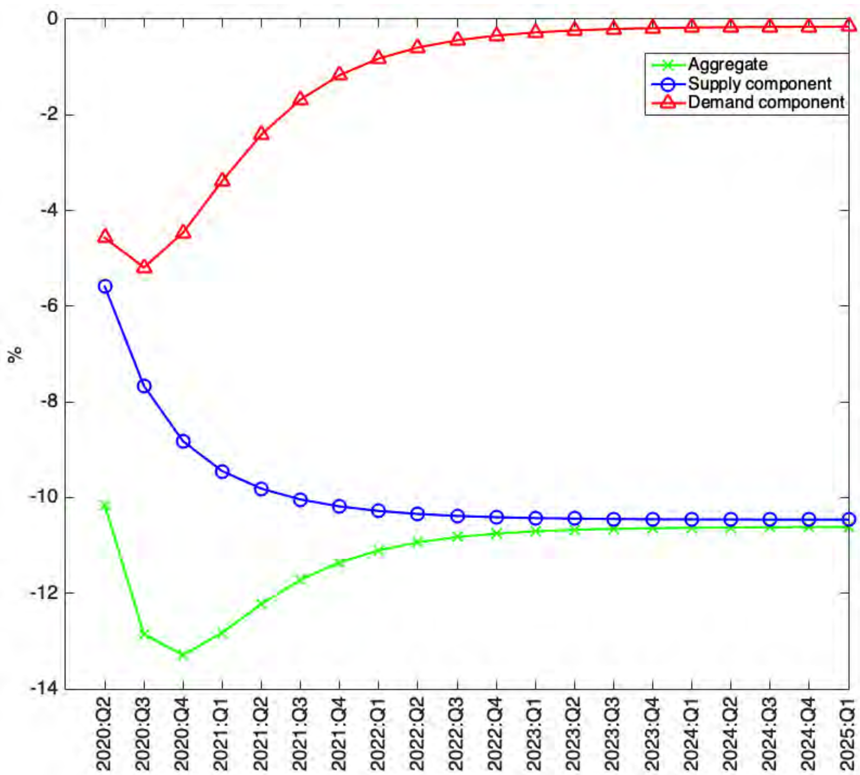
Figure 3 – VAR Cumulative Real GDP Growth Response to 2020:Q2 Demand and Supply Shocks. The VAR model is: $Y_t = AY_{t-1} + S[u_t^s, u_t^d]' + \Sigma\epsilon_t$, where Y_t is the vector of final, revised real GDP growth and inflation, $[u_t^s, u_t^d]'$ are pre-estimated structural shocks from the SPF, and $\epsilon_{t+1} \sim \mathcal{N}(\mathbb{0}_{2\times1}, \mathcal{I}_{2\times2})$. The model is estimated using quarterly data 1968:Q4-2019:Q2.



That said, the negative supply shock associated with the COVID episode could prove to be unusual in that the productive capacity of the economy could recover more quickly, for instance, if a vaccine becomes available relatively soon, or if businesses find creative ways to restore operations even in the presence of continued social distancing. Indeed, with SPF forecasts available for future quarters, the survey is consistent with a faster recovery. To demonstrate this, we compute the forecast revisions to future real GDP growth and inflation as $E_t[g_{t+n}] - E_{t-1}[g_{t+n}]$ and $E_t[\pi_{t+n}] - E_{t-1}[\pi_{t+n}]$, respectively, where

t=2020:Q2 and the data are available for n =1, 2, and 3 quarters. These revisions to the multi-period-ahead expectations are a natural extension of our definition of shocks to current quarter activity, and we interpret them as the expected reversal pattern following the 2020 COVID shock.

The top panel of Figure 4 illustrates the SPF-implied cumulative expected GDP growth until 2021:Q1 based on the 2020:Q1 (February) and 2020:Q2 (May) SPF's. The February survey predicted a steady growth of around 2 percent at an annual rate. The May survey suggests a strong drop in 2020:Q2 and a slow recovery: real GDP is not expected to catch up its pre-COVID-19 trend at least before 2021:Q1. The middle panel explicitly plots the forecast revisions that occurred between the February (2020:Q1) and May (2020:Q2) surveys suggesting that the recovery is expected to be "check mark"-shaped. The bottom panel of Figure 4 illustrates that both aggregate demand and aggregate supply components of cumulative GDP growth exhibit a "check mark"-trend as well. The AS component falls deeper but is also expected to recover faster. The relatively rapid recovery in the AS shock suggests that survey respondents anticipate that the supply-side of the economy may recover more quickly than average.

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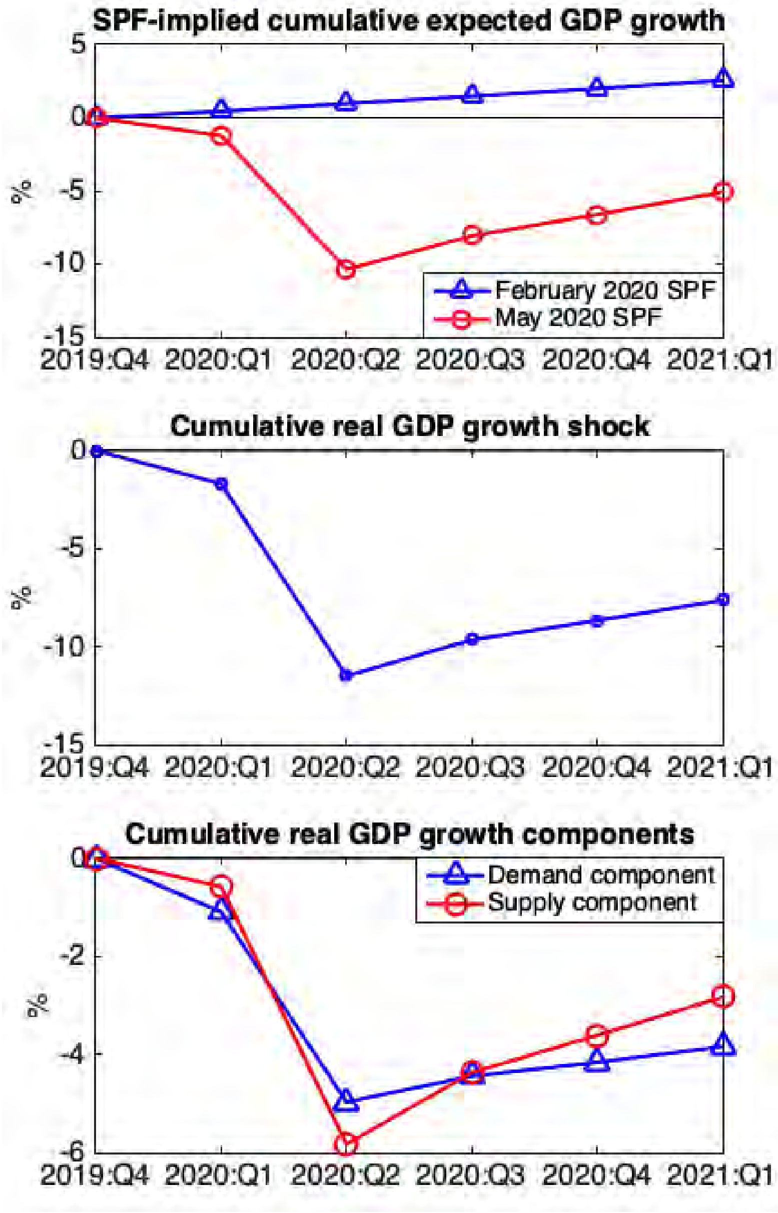
Figure 4 – Cumulative Real GDP Growth Shocks during COVID-19. The data is quarterly and not annualized. The starting point is the end of 2019:Q4. The aggregate demand component of the GDP growth is computed as σ_{gd} multiplied by the aggregate demand shock. The aggregate supply component of the GDP growth is computed as σ_{gs} multiplied by the aggregate supply shock.



The results in Figure 4 average survey responses across respondents, and, given the unprecedented nature of the situation, could mask important differences in the cross-section of responses. Figure 5 shows the full cross-sectional distribution of the expected recovery pattern from the SPF. For each quarter on the horizontal axis, the horizontal red line shows the median estimate. The blue bar shows the interquartile range for the cross-section, and the "+" symbols show the individual forecasts that fall outside of the interquartile range. Except for a couple of outliers, the cross-sectional distributions are generally rather tight. Every respondent continues to estimate that GDP growth fell 1.2 percent at a quarterly rate in 2020:Q1, consistent with the advance release from the BEA. The expected cumulative depth of the contraction in 2020:Q2 varies from -7 percent to -20 percent at a quarterly rate. All respondents expect that the level of real GDP will remain lower than the level achieved in 2019:Q4, with the most pessimistic forecasters projecting that real GDP will be at least 10 percentage points lower than the 2019:Q4 level.

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Figure 5 – Cumulative Real GDP Growth: Individual SPF Forecasts. The data is quarterly and not annualized. The starting point is the end of 2019:Q4. For each quarter on the horizontal axis, the horizontal red line shows the median estimate. The blue bar shows the interquartile range for the cross-section, and the "+" symbols show the individual forecasts that fall outside of the interquartile range.

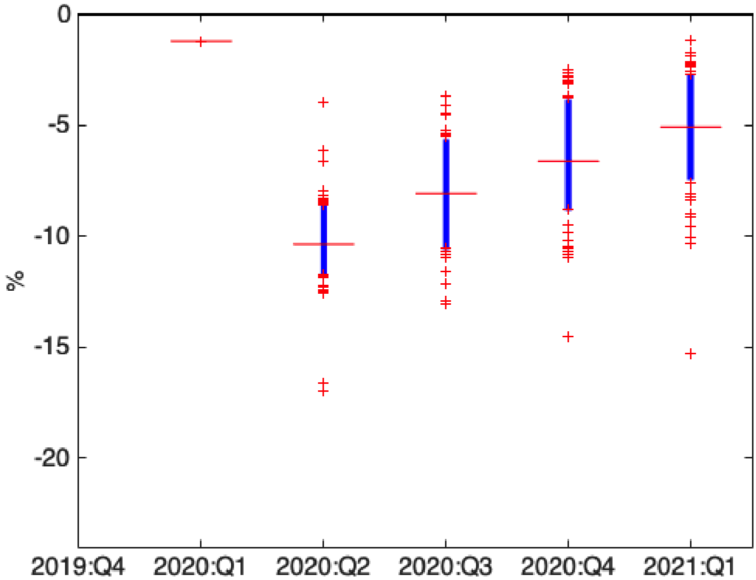

Figure 6 repeats the analysis of Figure 4 for inflation. The top panel suggests that the February 2020 SPF predicts a steady inflation of 2 percent annually while the May 2020 SPF expectation is 0 cumulative inflation over 2020 with the deflationary first half of the year. The middle panel plots our inflation forecast revision shock illustrating that the COVID-19 shock may have a permanent effect on the price level. The bottom panel indicates that the effect is mainly driven by the demand component.

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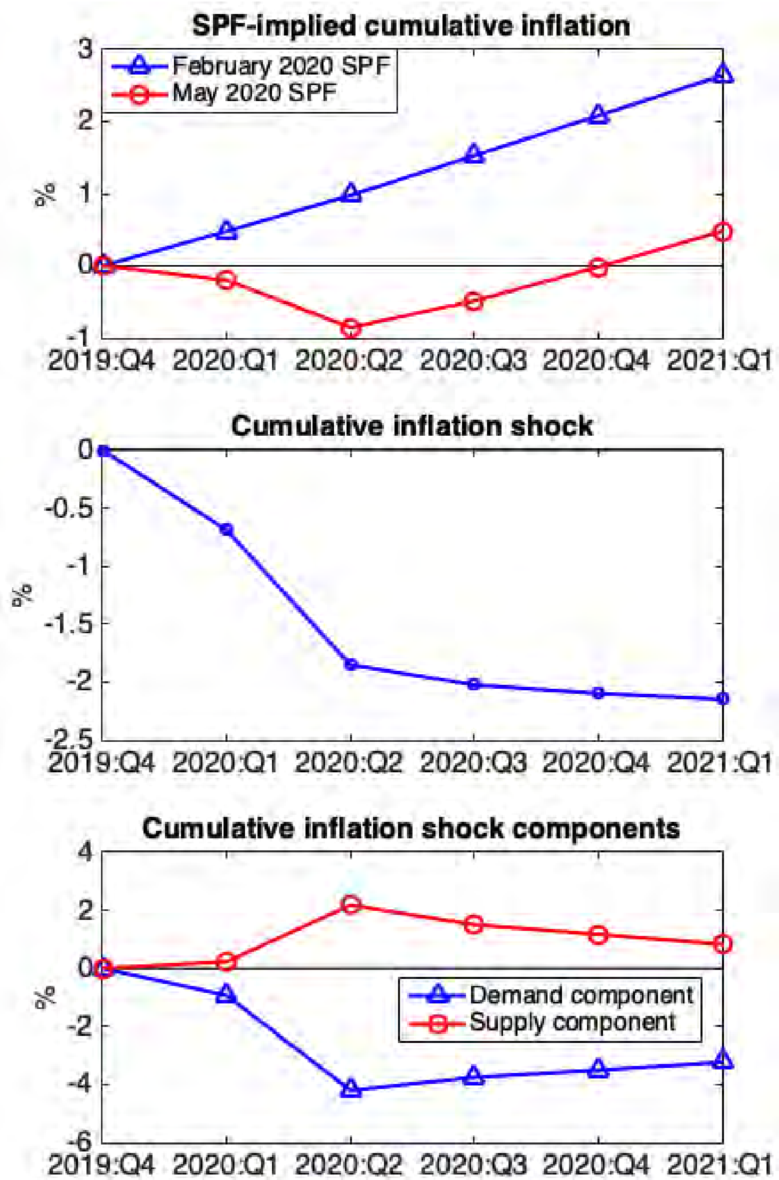
Figure 6 – Cumulative Inflation Shocks during COVID-19. The data is quarterly and not annualized. The starting point is the end of 2019:Q4. The aggregate demand component of the inflation is computed as $\sigma_{\pi d}$ multiplied by the aggregate demand shock. The aggregate supply component of the GDP growth is computed as $\sigma_{\pi s}$ multiplied by the aggregate supply shock.



5 Conclusion

We provide real-time estimates of aggregate demand and aggregate supply components of the COVID-19 recession. Our methodology requires minimal theoretical assumptions and relies only on non-Gaussian features of macroeconomic data which we show to be pronounced in our sample, even excluding the COVD-19 observations. Our calculations show that the 2020:Q1 real GDP growth shock is largely due to an aggregate demand shock, while the staggeringly large shock in 2020:Q2 was due to both aggregate demand and aggregate supply shock, but with the latter contributing somewhat more to the decline. A VAR analysis suggests a very slow recovery path of multiple years whereas surveys indicate a checkmark recovery, with the AS component actually recovering faster than the AD component.

Of course, as better macroeconomic data and more microeconomic data becomes available, these estimates might be substantially revised. An important goal of future empirical research is to study the propagation and interplay of aggregate demand and supply shocks (see, e.g., Guerrieri et al., 2020, or Caballero and Simsek, 2020, for a theoretical framework).

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The impact of communication on preferences for public policies: Evidence from a field experiment on the Covid-19 health-wealth trade-off

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How do people balance health/money concerns during a pandemic? And, how does the communication over this trade-off affect individual preferences? We address these questions using a hypothetical field experiment (randomized controlled trial, RCT) involving around 2000 students enrolled in a big university in the south of Italy. We compare four different framings in order to investigate whether a positive and more paternalistic framing which focuses on protective strategies ("safeguard") induces more conservative preferences than a more "crude" framing which focuses on potential losses ("costs"). We find that paternalistic framing on the health side induces individuals to give greater relevance to the health dimension. The effect is sizeable and stronger among females and altruistic individuals. Moreover, irrespective of the framing, we find a large heterogeneity in student's preferences over the trade-off. Economics students and students who have directly experienced the economic impact of the pandemic are found to favor polices that take in greater account the economic side of the tradeoff.

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1. Introduction

The strategies to manage Covid-19 pandemic involve a challenging trade-off for policy-makers. On the one hand, measures of social distancing - including a closure of economic activities - help to reduce the diffusion of the epidemic. On the other hand, they come at potentially huge economic costs.[1] For instance, in Italy, one of the countries most affected by the outbreak, it has been calculated that each week of closure of all non-essential activities caused a loss of the 0.5-0.75% of the GDP (Centro Studi Confidustria, 2020; Bank of Italy, 2020). Considering the period of lock-down observed in Italy, this translates into a reduction of the GDP of around 4-6% in just two months. Thus, it is obvious that a continuation of lock-down measures would be barely sustainable from an economic point of view.

For these reasons, the governments of many countries - including Italy - after a period of almost total shutdown of social and economic activities, started to plan a strategy for reopening (so called "phase two"). While different approaches are possible, typically all of them tend to combine a gradual restart of economic activities with precautionary individual behaviours (i.e. wash hands; avoid touching eyes, nose, mouth; stay at least two meters from other persons etc.) and preventive measures on the job-place (disinfection, staggered entrances, etc.) to control the diffusion of the infection. After the tough decision to stop non-essential economic activities until the emergency recovery, this is probably the most critical phase of the pandemic as it makes even more explicit the trade-off between health and economic issues.

Individual alignment to prescribed behaviours, already important during the initial phase of isolation and social distancing, is even more important during the restart of social and economic activities. Then, a communication strategy aimed to gain support and align individual preferences to government choices becomes crucial for a successful management of the pandemic. This paper investigates if and how different communication strategies affect individual preferences on the health/economy trade-off.

While during the initial phase of the epidemic the actions of the governments were quite exclusively focused on the health dimension, the management of the "phase two" focuses largely on the economic consequences of the pandemic and this can be inferred also from a significant change in the communication

[1] See for instance Gibson and Xiaojin (2020).

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strategy. For instance, on February 26th, the Italian's government bill including the closure of schools and many economic activities was presented by the ministry of Health as "Actions for the safeguard of community health"[2]. Conversely, on April 29th, the government launched the plan of "phase two" as a way to "address" the economic crisis caused by the pandemic.

To design effective strategies that properly balance these conflicting goals, it becomes very important to understand: how do people balance health/money concerns during a pandemic? And, how does the communication over this trade-off affect individual preferences for the restart during a pandemic?

We address these questions using a hypothetical field experiment (randomized controlled trial, RCT) involving around 2000 students enrolled in a big university in the South of Italy. During the period 20th April-25th April, i.e. before the start of "phase 2", we administered a survey that collects information on students' well-being during the pandemic, individual characteristics (demographics and socio-economic background variables), place of residence and self-reported measures of personality traits etc. The key question of the survey, used to answer our research question, asked to report preferences on health vs economic concerns for the management of the "phase two". We vary the introductory text of this question in order to investigate whether a positive and more paternalistic framing which focuses on protective strategies ("safeguard") induces more conservative preferences than a more "crude" framing which focus on potential losses ("costs").[3]

Pandemics affect virtually all aspects of life with considerable effects on individuals' welfare. This makes not clear *a priori* which communication strategy works better, especially in "phase two" when life gradually returns as it was before but the health threat is still in place. This might make more complicated the application of the *libertarian paternalism*, i.e. that of influencing people's choices so as to increase their welfare while at the same time respecting their freedom of choice (Thaler and Sunstein, 2003). Nonetheless, we find that preferences over the trade-off vary depending on how the trade-off is communicated. More precisely, we show that framing the decisions in terms of health safeguard and economic costs induces a large majority of students to give strong priority to the health dimension compared to the framing posing the issue

[2]Text of the press conference by the Italian ministry of health on February, 26th available here: http://www.salute.gov.it/portale/malattieInfettive/dettaglioNotizieMalattieInfettive.jsp?lingua=italiano&id=4086

[3] Recently, referring to health safeguard was quite common also in the Italian media. "La Repubblica", one of the main Italian newspapers, in February published 7 articles mentioning the phrase "health safeguard", which raised at 22 in March and reduced to 12 in April, when the government was programming the re-staring of economic activities. On the other hand, 118 articles published in March mentioned "the economic crisis", which raised to 228 in April.

in terms of costs: 47.36% of students answered that they would prefer policies that consider extremely or very much the safeguard of health and not much or a little bit the costs for the worsening of the economic situation. Conversely, under the cost framing, 34.15% of students answered that they would prefer policies that consider extremely or very much the costs for health and not much or a little bit the costs for the worsening of the economic situation. This is in line with a large empirical evidence showing that the framing strategy is highly relevant for the adoption of healthy behaviors (Bertoni, Corazzini, Robone, 2020) and that gain-framed messages exert a positive effect on health-enhancing activities such as walking and exercising (Mikels et al., 2016; O'Keefe and Jensen, 2007 for a review).

The health/money trade-off is also highly influenced by a number of features. Among those who give priority to the economic concerns, the field of study (economics students) and a difficult household's economic situation appear to be the main determinants. Moreover, individuals who feel worried for personal health and stressed when going out and those with altruistic feelings seem to give more weight to the health dimension.

Our finding that a paternalistic framing on the health side of the trade-off induces people to worry and care more about health provides useful insights to public authorities on how to tailor the policy message during the "phase two". Talking about the measures adopted using a protective framing for health conditions would induce people to weigh more health concerns and might increase their compliance with behaviors helping to control and limit the spread of the coronavirus. This would in turn allow policy makers to focus more on the economic consequences of the pandemic. So, such a costless strategy may help the government to manage "phase two" of the pandemic.

The rest of the paper is structured as follows. Section 2 describes the experimental design. Section 3 presents data and balance checks. Section 4 reports the results. Section 5 concludes.

2. Experimental design

We study the effect of different communication strategies on individual preferences regarding the trade-off between health and economic concerns by running a hypothetical field experiment (randomized controlled trial, RCT).

We manipulate the framing associated with the two elements of the trade-off comparing a positive and more paternalistic framing which focuses on the safeguard of health/economic conditions with a "crude"

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framing that presents the trade-off in terms of costs. The question used to impose treatment conditions is the following: “The government is planning the so-called “phase two”, that is the reopening after the temporary self-isolation measures introduced to deal with the coronavirus emergency. At this stage, it is necessary to consider the consequences that each decision has in terms of safeguard of (costs for) health - number of infections- and safeguard (costs for the worsening) of the economic situation. If you were the head of the government, which strategy would you choose?”. Respondent could choose among the following five alternatives: I would consider extremely the safeguard of (costs for) health and not much the safeguard (costs for the worsening) of the economic situation; I would consider very much the safeguard of (costs for) health and a little bit the safeguard (costs for the worsening) of the economic situation; I would take into account enough the safeguard of (costs for) health and enough the safeguard (costs for the worsening) of the economic situation; I would consider a little bit the safeguard of (costs for) health and very much the safeguard (costs for the worsening) of the economic situation; I would consider not much the safeguard of (costs for) health and extremely the safeguard (costs for the worsening) of the economic situation.

Thus, we design four treatments in a between-subjects design. In the first treatment, *HealthSafeguard-EconomyCosts* (HS-EC hereafter), participants are framed the trade-off in terms of safeguard of health and costs for the worsening of the economic condition. In the second treatment, *HealthCosts-EconomyCosts* (HC-EC, hereafter), participants are framed the trade-off in terms of costs both for heath and for the worsening of the economic condition. In the third treatment, *HealthSafeguard-EconomySafeguard* (HS-ES, hereafter), both elements of the trade-off are framed in terms of safeguard while in the fourth treatment, *HealthCosts-EconomySafeguard* (HC-ES, hereafter), the choice is between the costs for health and the safeguard of the economic situation.

Data are collected through an online survey submitted to about 10,000 students[4] enrolled at the University of Calabria[5] on April 20th and open until April 25th. Students have been randomly assigned to the

[4] These are students regularly enrolled at the 2nd and 3rd year of the different First Level Degrees, 1st year of the Second Level Degrees and all years of “Lauree a Ciclo Unico” offered by the University of Calabria, 61% of them are female and on average are 22 years old. 29% of them belong to the Department of Social Sciences, 20% to Engineering, 18% to Humanities and 33% to Sciences.

[5] The University of Calabria is a middle-sized public university located in the South of Italy. It has currently about 29,000 students enrolled in different Degree Courses and at different levels of the Italian University system. Since the 2001 reform, the Italian University system is organized into three main levels: First Level Degrees (3 years of legal duration), Second Level Degrees (2 further years) and Ph.D. Degrees. In order to gain a First Level Degree, students have to acquire a total of 180 credits. Students who have acquired a First Level Degree can undertake a Second Level Degree (acquiring 120 more credits). After having accomplished their Second Level Degree, students can apply to enroll for a Ph.D.

four treatment groups on the basis of their matriculation number.[6] Participation to the survey was voluntary and data were collected anonymously. Besides the treatment question, the survey included also information on personal characteristics (gender, age, studies, family background, and residence), personality traits and well-being. The response rate to our survey was 17.5%. Responded students seem to share similar characteristics with the whole population invited to join the survey, as shown in the next Section.

3. Data and Balance Checks

We use the question asking how individuals would balance health and economic concerns during the management of the "phase two" to create our dependent variable, *Trade-off*, which is an ordinal variable taking value from 0 (for participants who selected "I would consider not much the safeguard of (costs for) health and extremely the safeguard (costs for the worsening) of the economic situation") to 4 (for participants who selected "I would consider extremely the safeguard of (costs for) health and not much the safeguard (costs for the worsening) of the economic situation"). Thus, the variable is increasing in the importance given to health concerns and is on average 2.43 in the full sample. It takes on average the value of 2.4 in the treatment using costs for both elements of the trade-off or only for health, the value of about 2.6 when only health is expressed as safeguard and a lower value (2.3) when only economic concerns are expressed as safeguard.

As shown in Table 1, where we report descriptive statistics of our variables both overall and separately by treatment groups, students are on average 22 years old and about 71% of them are female. About 13% of the sample states to know someone (relatives, friends or even themselves) who tested positive for the diagnosis of Covid-19. Parents have studied on average for 12 years and for about 28% of students both parents became unemployed because of the Covid-19 emergency.

We have also asked student's current feelings, namely whether they are nervous when thinking about today's situation (*Irritable*, 65% of the sample), quiet and relaxed (*Quiet*, only 18% of the sample), stressed when having to go out (*Stress going out*, 44%) and worried about their own and their relatives health (*Worried*

However, in some degrees, such as Law and Architecture, the First and the Second Level Degrees are coupled together with a Degree (Lauree a Ciclo Unico) lasting 5 years.

[6] We have firstly divided students into two groups: those with an even matriculation number and those with an odd matriculation number. Then, within each group, we have randomly created two subgroups of equal dimension.

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Health – 56%, *Worried Health Others* – 91%)[7]. Finally, we included in the survey a question on psychological traits asking how much they see themselves as a person who is *Altruist* (21% of the sample), *Trustworthy* (29%), *Extroverted* (6%), *Sociable* (22%) and *Anxious* (13%).[8]

Table 1. Descriptive Statistics

	All (1)	*HC-EC* (2)	*HS-EC* (3)	*HS-ES* (4)	*HC-ES* (5)	*F (P-value)* (6)
Trade-off	2.4286	2.3902	2.5793	2.4027	2.3370	
	(0.6756)	(0.6853)	(0.7030)	(0.6704)	(0.6171)	
Sciences	0.3224	0.3060	0.2558	0.2434	0.4848	0.2274
	(0.4675)	(0.4613)	(0.4368)	(0.4296)	(0.5003)	(0.6340)
Humanities	0.1983	0.2239	0.2410	0.2743	0.0543	0.2252
	(0.3988)	(0.4173)	(0.4282)	(0.4467)	(0.2269)	(0.6356)
Engineering	0.1781	0.1885	0.2241	0.1881	0.1109	2.1357
	(0.3827)	(0.3915)	(0.4174)	(0.3912)	(0.3143)	(0.1454)
Social Sciences	0.3012	0.2816	0.2791	0.2942	0.35	1.3111
	(0.4589)	(0.4503)	(0.4490)	(0.4562)	(0.4775)	(0.2435)
Age	22.3061	22.2927	22.4524	22.2788	22.1957	0.3852
	(2.3514)	(2.2878)	(2.0591)	(2.2131)	(2.7867)	(0.5355)
Female	0.7086	0.7051	0.7040	0.7212	0.7043	0.2605
	(0.4545)	(0.4565)	(0.4570)	(0.4489)	(0.4568)	(0.6103)
Experienced Covid-19	0.1296	0.1441	0.1290	0.1261	0.1196	
	(0.3360)	(0.3516)	(0.3355)	(0.3323)	(0.3248)	
Parents' Education	11.7928	12.0477	11.7230	11.6637	11.7413	
	(3.3168)	(3.0079)	(3.4823)	(3.2946)	(3.4479)	
Parents Unemployed Covid-19	0.2761	0.2550	0.2537	0.3009	0.2957	
	(0.4472)	(0.4363)	(0.4356)	(0.4592)	(0.4568)	
People/mq	0.0377	0.0384	0.0381	0.0379	0.0362	
	(0.0228)	(0.0236)	(0.0223)	(0.0266)	(0.0179)	
Worried Health	0.5556	0.5499	0.5645	0.5509	0.5565	
	(0.4970)	(0.4981)	(0.4963)	(0.4980)	(0.4973)	
Worried Health Others	0.9129	0.9091	0.9112	0.9226	0.9087	
	(0.2821)	(0.2878)	(0.2847)	(0.2676)	(0.2883)	
Stress Going Out	0.4412	0.4479	0.4334	0.4403	0.4435	
	(0.4967)	(0.4978)	(0.4961)	(0.4970)	(0.4973)	
Irritable	0.6465	0.6319	0.6469	0.6549	0.6522	
	(0.4782)	(0.4828)	(0.4784)	(0.4759)	(0.4768)	
Quiet	0.1836	0.1729	0.1903	0.1881	0.1826	
	(0.3872)	(0.3786)	(0.3929)	(0.3912)	(0.3868)	
Altruist	0.2146	0.2217	0.2051	0.2367	0.1957	
	(0.4107)	(04159)	(0.4042)	(0.4255)	(0.3971)	
Trustworthy	0.2876	0.2860	0.3044	0.2566	0.3022	
	(0.4528)	(0.4524)	(0.4607)	(0.4373)	(0.4597)	
Extroverted	0.0561	0.0466	0.0550	0.0575	0.0652	
	(0.2302)	(0.2109)	(0.2282)	(0.2331)	(0.2472)	
Sociable	0.2228	0.2395	0.2030	0.2677	0.1826	
	(0.4162)	(0.4272)	(0.4026)	(0.4432)	(0.3868)	
Anxious	0.1313	0.1109	0.1416	0.1482	0.1239	
	(0.3378)	(0.3143)	(0.3491)	(0.3557)	(0.3298)	
Observations	1,836	451	473	452	460	

Notes: In columns (1) to (5) we report standard deviations in parentheses. In column (6) we report in parentheses *p*-values for the test of equality of means across treatments.

[7] Students were asked how much the statement (e.g. I am quite and relaxed) corresponded to their actual feeling and could choose among 5 alternatives: it doesn't match at all; it doesn't match; neither matches nor does not match; it matches; it matches completely. The variables are dummies taking the value of 1 when the answer is either "it matches" or "it matches completely" and 0 otherwise.

[8] Students could choose among 7 alternatives: completely disagree; very much disagree; somewhat disagree; neither agree nor disagree; somewhat agree; very much agree; completely agree. The variables are dummies taking the value of 1 when the answer is either "completely agree" and 0 otherwise.

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To investigate the effects that the four treatments produce on individual performance we need four comparable groups. The last column of Table 1 reports p-values of tests of equality of variables' means among treatments. Treatment groups are evenly balanced and data regarding predetermined characteristics show that we are unable to reject the hypothesis that the randomization was successful in creating comparable treatment groups as regards observable characteristics in the subsample of students submitting their answers to the survey.[9] Also, if we compare predetermined characteristics of respondents with those of the average student population we find that our sample is quite representative of the student population along the dimensions of age and field of study, while due to a higher response rate, women are slightly over-represented (61% of students included in the survey are female).

4. Results

In this section we carry out an econometric analysis to investigate whether being assigned to the four different framings adopted in our experiment induces individuals to balance differently health and economic concerns. In Table 2 to have an immediate picture of the effects, we simply report the percentage of students choosing each option under the four different treatments. The HS-EC treatment shifts individual preferences toward policies focusing on health concerns, while under the HC-ES, the option of equally considering both health and economic concerns records the highest percentage of preferences compared to all the other treatments.

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[9] We have also tested the equality of variables means for each possible pair of treatments. We find that treatments are always equally balanced in terms of age and gender but sometimes they present differences in the distribution of field of study. For this reason, in our estimates we control for dummies for field of study.

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Table 2. Relative frequencies of responses by treatments

	HC-EC	HS-EC	HS-ES	HC-ES
	A: costs for **B**: costs for the worsening	**A**: safeguard of **B**: costs for the worsening	**A**: safeguard of **B**: safeguard	**A**: costs for **B**: safeguard
I would consider extremely the **A** health and not much the **B** of the economic situation	7.76%	11.42%	7.74%	5.65%
I would consider very much the **A** health and a little bit the **B** of the economic situation	26.39%	35.94%	26.77%	24.35%
I would consider enough the **A** health and enough the **B** of the economic situation	63.86%	52.01%	64.16%	68.26%
I would consider a little bit the **A** health and very much the **B** of the economic situation	1.11%	0.42%	0.66%	1.52%
I would consider not much the **A** health and extremely the **B** of the economic situation	0.89%	0.21%	0.66%	0.22%

In order to better investigate how our different treatments affected individual preferences, we estimate several specifications of the following simple model:

$$[1]\ HealthCenteredPolicy_i = \beta_0 + \beta_1(HS - EC)_i + \beta_2(HC - ES)_i + \beta_3(HS - ES)_i + \beta_4 X_i + \beta_5 F_i + \beta_6 W_i + \beta_7 Z_i + u_i$$

where the vector X_i includes individual pre-determined characteristics (gender, age, field of study etc.), F_i includes family background variables (parents' education and employment, experience with Covid-19 and house comfort), W_i is a set of variables measuring current physical and psychological health, Z_i are individual psychological traits and u_i is the error term.

In this setting, β_1 is the difference between HS-EC and HC-EC (that is the treatment effect of framing health in terms of safeguard instead of costs) in the propensity to favor policies that give higher weight to health concerns arising from the spread of the Covid-19. Positive values of β_1 suggest that, in the management of "phase two", communicating the trade-off using for health a positive and more paternalistic framing which focuses on protective strategies - instead of a more "crude" framing based on costs - increases individuals' concern for the health consequences of the pandemic. A similar interpretation holds for β_2 and β_3 that represent the effect induced by the other two treatments HC-ES and HS-ES, respectively, with respect to the framing HC-EC.

Our hypotheses are the following:

- H1: $\beta_1 > 0$, that is the use of a positive framing (safeguard) for health induces individuals to associate a higher weight to health in the trade-off thus leading to a more conservative behaviour;

- H2: $\beta_2 < 0$, that is the use of a positive framing (safeguard) for economic concerns will increase the weight of economic concerns in the trade-off;

- H3: $\beta_3 \geq 0$, that is when both elements of the trade-off are framed in terms of safeguard, either they should carry the same weight or, given the strong health concerns under a pandemic, the safeguard of health may carry more weight.

In Table 3 we report estimation results of several specifications of model [1]. We estimate an Ordered Probit Model to study the effect of the assigned treatment condition on the probability of students to give higher relevance to health concerns in policy decisions. Since the dependent variable increases with the importance associated with health concerns, positive coefficients suggest the likelihood of preferences more shifted toward health concerns. In all the regressions, standard errors (corrected for heteroskedasticity) are reported in parentheses.

As shown in column (1), where we do not include controls, we find that, compared with the HC-EC treatment, the HS-EC framing induces individuals to choose a policy that gives greater relevance to health issues. Thus, our data confirm hypothesis H1. The shift in preferences that favor policies that mainly focus on health issues produced by the HS-EC treatment is statistically significant also when compared with the other different types of framing used in our experiment. As regards the hypothesis H2, we find evidence of a negative effect of the positive framing associated with economic concerns on the preference for health-oriented policies, but the estimated coefficient is not statistically significant. Finally, when looking at the HS-ES treatment (H3), we find a positive but not statistically significant coefficient. This would suggest that framing both elements

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of the trade-off in terms of safeguard is the same as using the framing "costs" and, even under a pandemic, the safeguard of health does not carry significantly more weight when joined with the safeguard of the economic situation.

The impact of the HS-EC treatment is sizeable. When looking at average marginal effects for the specification including all the control variables (column 6) we find that when the trade-off is expressed in terms of safeguard of health and costs for the worsening of the economic situation - instead of in terms of costs for both health and the economy- individuals are about 0.5% less likely to choose the policy giving the highest weight to the economic situation; about 0.7% less likely to choose the policy considering a little bit health and very much the economic situation; 11.4% less likely to choose the intermediate policy; 7.5% more likely to choose the policy considering very much health and a little bit the economic situation and about 5.1% more likely to choose the policy that gives highest weight to health concerns.

These results remain qualitatively unchanged when we add controls for a number of demographic characteristics, such as gender, age, field of study, socio-economic background, for psychological traits and perception of the Covid-19 crisis.

As regards control variables, we find that the field of study reveals different preferences and that students enrolled in scientific disciplines tend to prioritize health concerns compared with students enrolled in economics and social sciences and engineering. There is also an important difference in terms of socio-economic background: students who have more educated parents show a preference for policies that tend to favor health protection. Since parental education is usually associated with the economic conditions of the family, the result shows that those who come from contexts of greater distress tend to give greater weight to the economic costs of the pandemic.[10] This is also confirmed by the fact that students with parents who lost their jobs due to the emergency tend to express themselves more favorably towards a compromise that takes due account of the economic costs of the crisis. Finally, we find that students who are particularly worried for their health due to the Covid-19, those who feel stressed to go out and those who describe themselves as altruistic are more favorable to policies more focused on health issues.

To check the robustness of our results, we have also created as outcome variable a dummy taking the value of 1 for individuals who report to prefer policies that give very less or less relevance to the economic

[10] For heterogeneous impact of the pandemic for different categories of workers see for instance Montenovo et al. (2020).

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costs of the crisis and 0 otherwise. Probit estimates are qualitatively very similar to those discussed above. The only difference concerns the HC-ES coefficient that now is more precisely estimated but still typically not statistically significant at conventional levels. Results are not reported and available upon request.

Table 3. The Impact of communication on preferences for policies aimed at managing the Covid-19 crisis. Ordered Probit Estimates

	Trade-off					
	(1)	(2)	(3)	(4)	(5)	(6)
HS-EC	0.3241***	0.3349***	0.3390***	0.3449***	0.3475***	0.3480***
	(0.0771)	(0.0769)	(0.0772)	(0.0781)	(0.0782)	(0.0783)
HC-ES	-0.0998	-0.1159	-0.1191	-0.1072	-0.1153	-0.1154
	(0.0791)	(0.0809)	(0.0808)	(0.0814)	(0.0818)	(0.0818)
HS-ES	0.0251	0.0373	0.0381	0.0430	0.0451	0.0413
	(0.0799)	(0.0798)	(0.0799)	(0.0805)	(0.0807)	(0.0809)
Sciences		0.2453***	0.2502***	0.2391***	0.2511***	0.2527***
		(0.0690)	(0.0690)	(0.0693)	(0.0704)	(0.0705)
Humanities		0.1100	0.1125	0.1155	0.0998	0.0939
		(0.0840)	(0.0844)	(0.0850)	(0.0853)	(0.0853)
Engineering		0.0797	0.0725	0.0676	0.0692	0.0749
		(0.0832)	(0.0870)	(0.0878)	(0.0887)	(0.0889)
Age			-0.0200	-0.0210	-0.0232*	-0.0232*
			(0.0131)	(0.0132)	(0.0132)	(0.0132)
Female			-0.0125	-0.0103	-0.0813	-0.0905
			(0.0667)	(0.0670)	(0.0713)	(0.0715)
Experienced Covid-19				0.0759	0.0505	0.0513
				(0.0861)	(0.0852)	(0.0851)
Parents' Education				0.0178**	0.0195**	0.0196**
				(0.0085)	(0.0085)	(0.0086)
Parents Unemployed Covid-19				-0.1442**	-0.1396**	-0.1410**
				(0.0632)	(0.0634)	(0.0637)
People/mq				2.8579**	2.7593**	2.7032**
				(1.3145)	(1.3219)	(1.3268)
Worried Health					0.1785***	0.1718***
					(0.0586)	(0.0590)
Worried Health Others					0.0682	0.0603
					(0.1210)	(0.1210)
Stress Going Out					0.1370**	0.1288**
					(0.0563)	(0.0570)
Irritable					0.0312	0.0258
					(0.0648)	(0.0654)
Quiet					-0.0203	-0.0242
					(0.0818)	(0.0824)
Altruist						0.1395*
						(0.0783)
Trustworthy						-0.0353
						(0.0660)
Extroverted						0.0667
						(0.1276)
Sociable						-0.0256
						(0.0779)
Anxious						0.0411
						(0.0901)
Province of Residence FE	NO	NO	NO	YES	YES	YES
Observations	1836	1836	1836	1836	1836	1836

Notes: Standard errors (corrected for heteroskedasticity) are reported in parentheses. The symbols ***, **, * indicate that the coefficients are statistically significant at the 1, 5 and 10 percent level, respectively.

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In table 4 we inquire whether treatment effects differ according to a number of individual characteristics. We firstly focus on gender and include among regressors the interaction term between the three different treatment statuses and the dummy *Female*. As shown in column (1), we find that the positive effect of the HS-EC treatment on student's preferences over policies that mainly focus on health concerns is mainly due to females' reactions. The effect of this treatment on male preferences is positive but not statistically significant; instead, we find a positive and highly statistically significant impact on female preferences.

In column (2) we consider parents' education (demeaned) and find a differentiated effect for the HS-ES treatment with students whose parents are well educated (an average number of years of education above the mean of 12) showing preferences more in favor of policies focusing on health concerns also when faced with the HS-ES treatment.[11]

In column (3) we analyze whether altruistic individuals, who according to estimates shown in Table 3 tend to prefer policies that focus on health issues, react to the treatments differently from other individuals. We find that the HS-EC treatment produces a stronger effect on these individuals, while no statistically significant differences emerge for the other treatments.

We have also performed other heterogeneous treatment effect analyses. First, we have considered whether students having parents who have lost their job due to the pandemic reacted differently to the various framings. We find some evidence that they are more likely to prefer a policy that is more shifted towards the economic side when framing is focused on the safeguard of the economic conditions (HC-ES). However, the effect is never significant at conventional levels. Second, we have considered whether individuals more directly exposed to the Covid-19, because relatives or friends tested positive to the virus, are less or more influenced by framing. We do not find any statistically significant difference, the only relevant difference (even if not statistically significant when including all the covariates) concerns the effect of the HC-ES treatment that for individuals who have more closely experienced the epidemic does not seem to induce preferences more in favor of policies that tend to limit the impact of the crisis on the economy. These results are available upon request.

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[11] We have also tried to see whether effects were heterogeneous according to the number of squared meters available for each person in the house but we did not find any effect.

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Table 4. Heterogeneous effects. Ordered Probit Estimates

	(1)	(2)	(3)
HS-EC	0.0683	0.3436***	0.2779***
	(0.1459)	(0.0783)	(0.0880)
HC-ES	-0.2387	-0.1206	-0.1360
	(0.1516)	(0.0819)	(0.0901)
HS-ES	-0.0590	0.0413	0.0217
	(0.1571)	(0.0808)	(0.0911)
HS-EC *Female	0.4009**		
	(0.1727)		
HC-ES *Female	0.1769		
	(0.1782)		
HS-ES *Female	0.1476		
	(0.1836)		
HS-EC * Parents' Education (demeaned)		0.0278	
		(0.0235)	
HC-ES * Parents' Education (demeaned)		0.0336	
		(0.0247)	
HS-ES * Parents' Education (demeaned)		0.0648**	
		(0.0257)	
HS-EC *Altruist			0.3251*
			(0.1911)
HC-ES *Altruist			0.0838
			(0.2032)
HS-ES *Altruist			0.0908
			(0.1954)
Female	-0.2763**	-0.1012	-0.0893
	(0.1306)	(0.0714)	(0.0714)
Parents Unemployed Covid-19	-0.1447**	-0.1388**	-0.1417**
	(0.0637)	(0.0635)	(0.0636)
Parents' Education (demeaned)		-0.0131	
		(0.0186)	
Altruist	0.1494*	0.1418*	0.0096
	(0.0785)	(0.0787)	(0.1454)
Observations	1836	1836	1836

Notes: Standard errors (corrected for heteroskedasticity) are reported in parentheses. The symbols ***, **, * indicate that the coefficients are statistically significant at the 1, 5 and 10 percent level, respectively.

5. Conclusions

After a long period of lock-down, many countries - even with some differences and peculiarities - are entering or are programming to enter in the so-called "phase two" of the Covid-19 pandemic. As this phase combines gradual return to economic activities with a co-existence with the virus, it requires addressing an implicit trade-off between the health and economic concerns of the pandemic.

In this paper, we investigate how people balance this trade-off during the pandemic and how the communication strategy over this trade-off affects their preferences upon policies aimed at managing the restart of economic and social activities. We analyze this issue in Italy - one of the country most affected by the outbreak - using a hypothetical field experiment involving around 2000 students enrolled in a big University in the South of Italy. Data are collected through a survey administered during the period 20th April-25th April, i.e. before the start of "phase two". We compare a framing which focuses on protective strategies ("safeguard") with a more "crude" framing which focuses on potential losses ("costs").

We find that a policy talking about the safeguard of health and the costs for the worsening of the economic situation induces individuals to give greater relevance to health issues than when the trade-off is expressed in terms of costs for both health and the economy. The effect is sizeable and stronger among females and altruistic individuals. To give an idea of the magnitude, we find that while 47.36% of students answered that they would consider extremely or very much health when framed as safeguard versus economic costs, this share is 34.15% in the group having both health and economic issues framed as costs. Also, students whose parents are more educated than average tend to favor policies focusing on health concerns also when both health and economic issues are framed as safeguard. Framing only economic issues in terms of safeguard seems to increase preferences for a policy that is more shifted on the economic side but the effects is never significant at conventional levels.

These results have important policy implications. First, they suggest that the communication strategy during an emergency - such as that deriving from the diffusion of the Covid-19 virus - plays a crucial role and that a more paternalistic communication that focuses on the "safeguard" of the health conditions is likely to significantly shape the individual preferences over the health dimension of the crisis. If we assume no significant deviations from stated *vs* revealed preferences, we may speculate that a more paternalistic communication is likely to increase political consensus and may represent a costless strategy to ensure higher compliance with political recommendations over the "phase two". Second, our paper shows a large degree of heterogeneity in the preferences over the health-money trade-off during the pandemic. Some of these differences are related to personal attitudes and/or specific knowledge (i.e. the field of study) and to state-dependent conditions (i.e. personal or familiar experience with the Covid-19). However, there are marked differences due to socio-economic background that may pose important policy concerns. Political debate in many countries is nowadays dominated by very polarized positions over the priorities to give to the management of the "phase two". Our paper suggests that these differences might be explained by the asymmetric economic consequences of the pandemic. One implication of this result is that financial help

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towards people who faced large economic shocks may be also supported as a way to strength social cohesion and preferences alignment over the management of the pandemic. Lastly, we find an interesting gender differential in the preferences over the trade-off that might deserve further exploration. Despite the fact that the health consequences of the Covid-19 virus seem to be less pronounced among females, we find that women are significantly more affected by a paternalistic framing focusing on the safeguard of the health conditions. Whether this depends on altruistic preferences (i.e. worry about other's health) or on the role model of the male breadwinner might be a nice area of future research.

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Wage inequality and poverty effects of lockdown and social distancing in Europe[1]

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The "social distancing" measures taken to contain the spread of COVID-19 impose economic costs that go beyond the contraction of GDP. Since different occupations are not equally affected, this supply shock may have distributional implications. Here, we evaluate the potential impact of enforced social distancing on wage inequality and poverty across Europe. We compute a Lockdown Working Ability (LWA) index which represents the capacity of individuals to work under a lockdown given their teleworking index –that we obtain for European occupations using 2018 EU-LFS– and whether their occupation is essential or closed. Combining our LWA index and 2018 EU-SILC, we calculate individuals' potential wage losses under six scenarios of lockdown. The Lockdown Incidence Curves show striking differential wage losses across the distribution, and we consistently find that both poverty and wage inequality rise in all European countries. These changes increase with the duration of the lockdown and vary with the country under consideration. We estimate an increase in the headcount index of 3 percentage points for overall Europe, while the mean loss rate for the poor is 10.3%, using the 2 months lockdown simulation. In the same scenario, inequality

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measured by the Gini coefficient increases 2.2% in all Europe, but more than 4% in various countries. When we decompose overall inequality in Europe into between- and within-countries components, both elements significantly increase with the lockdown, being the change of the latter more important.

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1. Introduction

The dramatic and unprecedented intensity of the shock due to the Covid-19 pandemic has highlighted the importance of measuring the economic consequences of "social distancing". The lockdown measures implemented in many countries around the world will likely have a significant negative impact on their GDP (IMF, 2020). Thus, the latest forecasts collected by Consensus Economics point towards expectations of a sharp mean decline in GDP of 5.7% in the euro area this year (see also Florian et al., 2020). However, the effect of the pandemic will not only take place at the aggregate level and is likely to have distributional implications (Furceri et al., 2020). The social distancing imposed by governments to limit the spread of the pandemic has caused an asymmetric effect on the labour market: discounting essential occupations like health services and food sales, only the jobs not closed by the lockdown that can be done from home ("teleworkable") will be not impeded. This asymmetry of the supply shock implies that the economic costs of social distancing could be significant, not only in terms of negative GDP growth rates but also in terms of higher wage inequality and poverty rates. In this paper, we analyse the potential effects of social distancing on wage inequality and poverty in absence of any public policy across Europe.

Recent studies have provided estimates of the supply shock caused by the emergency regulation imposed to contain the spread of Covid-19 (Dingel and Neiman, 2020; Hicks, 2020; and Koren and Petö, 2020) They have evaluated the possible economic consequences of social distancing –without considering the subsequent effects that may occur on the demand side– by calculating to what extent occupations can be performed from home (teleworking). Mongey et al., 2020 find that workers with less ability to work from home had been indeed more unable to follow the 'stay at home advice' -using geolocation data- and that they have suffered higher unemployment increases. In a more comprehensive analysis, del Rio-Chanona et al. (2020) provide quantitative predictions of first order supply and demand shocks associated with the Covid-19 pandemic. These studies, mainly focused on the U.S. economy, have analysed the consequences of social distancing in the job market, at the occupation and industry levels, without delving into the study of wage inequality. We find two exceptions. First, Irlacher and Koch (2020) obtain a substantial wage premium (higher than 10%) in a Mincer regression for German

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workers performing their job from home and a lower share of teleworkable occupations in poorer German regions. Second, Brunori et al. (2020) study the short-term effects that two months of lockdown have had on the Italian income distribution. By using a static microsimulation model, they find a non-negligible increase of poverty and inequality in Italy.

To estimate the impact of social distancing on wage inequality and poverty across Europe, we focus on the supply-side reductions due to the closure of non-essential occupations and workers not being able to perform their activities at home. Despite their relevance, our analysis does not consider the demand-side changes due to individuals' response to the pandemic, nor the subsequent second-order effects in supply (additional reductions as shortages propagate through supply chains) and in demand (as workers who are laid off or at risk experience a reduction in income). While these demand and second order effects are difficult to estimate at this early stage, the first order restrictions imposed in the lockdown provide a clear framework to study the consequences for inequality and poverty of having a particular productive structure. Under a lockdown, the asymmetry of the supply-side restrictions may affect economies in a different way just because their productive structure is not the same: countries who are specialised in outdoor and non-essential activities like tourism and construction will, in principle, suffer more from the lockdown. We thus restrict ourselves to measuring the potential impact on wage inequality and poverty of enforced social distancing.

In general, if occupations with higher wages are more teleworkable, we should observe an increase in wage inequality due to lockdown within each country analysed. However, whether this happens, and the intensity of this change, will depend on the structure of the economy and the extent of essential and closed occupations under the lockdown. The wide set of European countries in our sample –with a variety of productive structures– will also allow us to test if different productive structures imply different potential effects on wage inequality and poverty under lockdown and compulsory social distancing. Note that if that is the case, inequality would not only increase within countries, but also between nations, which could exacerbate the problem of cohesion in Europe.

The first step to measure the changes in wage inequality and poverty across Europe due to lockdown is to calculate the index of teleworking at the occupational level. Dingel and

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Neiman (2020) found that 37 percent of jobs in the United States can be done entirely from home. What is the share of occupations that allow teleworking in Europe? Following these authors, we use fifteen questions from the Occupational Information Network (O*NET) database (compiled by the United States Department of Labour) such as, 'is the work done outdoors?' or, 'does it require significant physical activity?' to calculate the probability of teleworking for each occupation. We then use the 2018 European Union Labour Force Survey (EU-LFS) occupational structure to translate these probabilities into the European context. Finally, we match the EU-LFS occupation teleworking index and the 2018 European Union Statistics on Income and Living Conditions (EU-SILC), which provides detailed information on wage at the individual level. After this procedure, we have for every worker in the EU-SILC database the individual index of teleworking (according to her occupation) and the wage.

A lockdown implies that some activities –like healthcare or food chain related jobs– will become essential while others will be closed. When the occupation is essential, workers will be not affected by lockdown regardless of their capacity to work from home. When a certain economic activity is closed –like hospitality– working is not at all possible, and teleworking does not matter. For the remaining economic activities, only teleworking is allowed. Consequently, during the lockdown we need to adjust our index of teleworking for the workers whose occupation is essential or closed, to obtain an individual measure that summarizes the capacity of each worker to keep active under the lockdown. We will call this measure Lockdown Working Ability (LWA) index.

The next step is to calculate the potential wage loss due to the lockdown. Because not all workers are able to perform their job at home and some activities are closed, there will be wage reductions for a significant part of the labour force. To simulate these wage losses, we consider six possible scenarios: *i*) one month of lockdown; *ii*) two months of lockdown; *iii*) four months of lockdown; *iv*) one month of lockdown and six months of only partial functioning of the closed activities (80% of capacity); *v*) two months of lockdown and six months of partial functioning of the closed activities; and, *vi*) four months of lockdown and six months of partial functioning of the closed activities. With this proposal we intend, on the one hand, to measure the effect of enlarging the lockdown and, on the other hand, to calculate the impact of medium-term regulation imposed to

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contain the spread of Covid-19 during the de-escalation. Although each European country may have followed slightly different lockdown and de-escalation strategies, the core of the social distancing enforcing policies has been similar in most of them. For that reason, and to ensure that in our analysis differences across countries are exclusively due to their productive structure, we simulate the same six scenarios for all European countries.

The last step is to measure the changes in wage inequality and poverty across countries, and the variation of wage inequality between and within-countries due to the lockdown. For this task, we first compute the Lockdown Incidence Curve (LIC), which represents the relative change in the wage of individuals ordered by centiles, and the related changes in the mean 'growth' rate of the poor (Ravallion and Chen, 2003) and headcount index. Then, we use the Gini coefficient and the Mean Logarithmic Deviation (MLD) to calculate the changes in wage inequality. The first measure is a popular index of inequality which is widely used in the literature, while the second measure fulfils some properties which are necessary for our analysis of inequality decomposition. In particular, the MLD is the only inequality index that is additively decomposable into a between-group and a within-group component (Bourguignon, 1979; Shorrocks, 1980) and has a path-independent decomposition (Foster and Shneyerov, 2000).

Our first result is that average teleworking varies significantly not only across countries, going from 0.24 in Romania to 0.48 in Denmark, but also by gender, type of work (full or part time), type of contract (permanent or temporary) and level of education. Secondly, the average of teleworking in a country is positively correlated with the average annual salary, while within-countries inequality of teleworking is negatively associated with the average annual salary. The positive correlation of teleworking and wages is found not only at the country level but also at the individual level.

When the lockdown scenarios are in place, and only essential and non-closed teleworkable occupations can work, we estimate that poverty increases for the headcount index and the mean loss rate of the poor in all countries for all simulations. For example, under a lockdown of two months, we observe that the headcount index increases 3 percentage points in overall Europe, while the mean loss rate for the poor increases 10.3%. However, these changes vary greatly with the country under consideration. The same patterns are observed when we represent the LICs across Europe. According to these

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curves, the highest increases in poverty are found in Cyprus, while the smallest ones happen in Romania regardless of the simulation scenario assumed. Likewise, wage inequality increases for the Gini coefficient and the MLD in all countries for all simulations. For example, under a lockdown of two months, the changes in the Gini and MLD indices are 2.2% and 10.1% for Europe as a whole, respectively. We thus find that poverty and inequality changes are sizeable in all countries and they increase with the duration of the lockdown and the partial closure of some activities.

When we decompose overall inequality in Europe, both within countries and between countries inequality increase with the duration of the lockdown and the partial closure of some activities, producing a double process of divergence in wage inequality in Europe. But this increase in wage dispersion is not symmetric, and the within-countries inequality component increases more than the between-countries inequality component (5.0% and 2.4% respectively, under a lockdown scenario of two months). Although cohesion between European countries decreases with the lockdown, the main wage inequality change happens within European countries.

The rest of the paper is structured as follows. In Section 2 we present the databases used to calculate our teleworking index and comment on the values of this index for the European countries. The methodology applied to calculate the changes in wage inequality is described in Section 3. In Section 4 we highlight the main results obtained for Europe. Finally, Section 5 concludes.

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2. The databases and the index of teleworking in Europe

In this study we use three different databases, all of them necessary for our combined analysis of working ability during the lockdown and changes in wage. First, we obtain information about the key attributes and characteristics of occupations from the American O*NET database, necessary to assess occupational teleworking ability. Second, we use the latest 2018 wave of EU-LFS (2020 release) –with detailed employment and occupational information for European countries– to accurately obtain occupational teleworking information for the European occupational categories. Finally, this information is combined with the rich socioeconomic data –crucially, salaries– from the

2018 wave of EU-SILC (2020 release). Before we explain the procedure followed to calculate the teleworking index, the above-mentioned databases are described in detail.

2.1. The databases

The O*NET database is the primary project of the O*NET program promoted by the US Department of Labour, and replaces the Dictionary of Occupational Titles (DOT), which was used for earlier research. O*NET analysts at the Department of Labour assign scores to each task according to standardized guidelines to describe their importance within each occupation. Thus, O*NET is a source of occupational information, providing data on key attributes and characteristics –from which teleworking capacity can be derived– for 968 occupations, based on the Standard Occupation Classification 2010 (ONET-SOC2010). Therefore, for this information about occupations to be used in our analysis, we will have to translate O*NET-SOC2010 data into European codification ISCO-08 used in EU-LFS (at the 3-digit level) and EU-SILC (at the 2-digit level).

EU-LFS, which we will use to translate O*NET teleworking indices into European coding, compiles national labour force surveys carried out by the national statistical authorities and is homogenised by Eurostat. This database includes information on the labour market status of the 28 European Union countries, plus Norway, Switzerland, Iceland, Turkey, and Macedonia. These last three countries are not considered in our analysis, as they are not included in the current EU-SILC 2020 release that we use for our wage inequality analysis. Malta is also discarded because the occupation variable is only available at the International Standard Classification for Occupations (ISCO-08) 1-digit level, lacking enough precision for our analysis (see Table A1 in Appendix A).

In this work, we use EU-LFS (2018) where employment is measured according to the International Labour Organization (ILO) definition.[2] Occupations are coded at the 3-digit level (ISCO-08) and industries are coded at the 1-digit level with the Nomenclature Statistique des Activités Economiques dans la Communauté Européenne (NACE)

[2] Employment –and therefore occupational shares– can be measured either by thousands of persons employed (given by the EU-LFS survey weights) or by thousands of weekly hours worked (EU-LFS survey weights multiplied by usual weekly hours), we use the former definition in our EU-LFS analysis.

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revision 2.[3] We drop the occupation “Subsistence farmers, fishers, hunters, and gatherers” (ISCO-08 63) , since employment occurs only in a small number of countries (suggesting classification problems), and the industry “Activities of extraterritorial organisations and bodies” (NACE. Rev.2 U) because the number of observations is scarce. We also discard “Armed forces occupations” (ISCO-08 0) as O*NET does not facilitate information on those occupations and “Unpaid family workers” that has very few observations. While EU-LFS is the best database to map the occupations (and teleworking indices) from O*NET it lacks the wage information crucial for our inequality analysis. For this reason, we will merge EU-LFS teleworking indices for each ISCO-08 occupation with the EU-SILC database which provides detailed microdata on wages.

EU-SILC encompasses homogeneous surveys on living conditions implemented by the national institutes of statistics under the coordination of Eurostat. Collected data contains information on a wide range of socioeconomic items, including occupation, industry and salary at the personal level. Taking advantage of this information, we will sample active workers −employees and self-employed– who declare to be working at least part time at the time, and who have a greater than zero salary during the reference year. This excludes unemployed and retired workers, and people under the legal working age of 16. For our salary variable, for each individual we have aggregated yearly cash and in-kind gross employee income and gross self-employed income. Employee income is defined as ‘the total remuneration payable by an employer to an employee in return for work done by the latter during the income reference period’, while self-employed income is the gross income received during the reference year as a result of their current or former involvement in self-employed work. As for the occupational information, this is typically coded at the 2-digit level (ISCO-08), while industries are coded at the 1-digit level (NACE Rev.2) in EU-SILC.[4] Consequently, we have to aggregate the occupations at the 3-digit level (ISCO-08) in EU-LFS to the 2-digit level (ISCO-08) before we can match both databases (see Table A1 in Appendix A).

[3] For Bulgaria, Poland, and Slovenia occupations are coded at the ISCO-08 2-digit level. Industries are not disaggregated for Denmark (see Table A1). We describe the set of industries NACE (1-digit level) and of occupations ISCO-08 (2-digit level) in Tables B1 and B2, respectively (see Appendix B).
[4] For Germany and Slovenia occupations are coded at the ISCO-08 1-digit level (see Table A1).

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2.2. Measuring teleworking

Following Dingel and Neiman (2020), the responses to two O*NET surveys were used: "work context" and "generalized work activities".[5] From "work context" the following items were retained:[6]

- How frequently does your current job require electronic mail? (Q4)
- How often does your current job require you to work outdoors? (Q17)
- How often is dealing with violent or physically aggressive people part of your current job? (Q14)
- In your current job, how often do you wear common protective or safety equipment such as safety shoes, glasses, gloves, hearing protection, hard hats, or life jackets? (Q43)
- How much time in your current job do you spend walking or running? (Q37)
- How often does your current job require that you be exposed to minor burns, cuts, bites, or stings? (Q33)
- How often does your current job require that you be exposed to diseases or infection? (Q29)

From "generalized work activities" the following items were considered:[7]

- How important is Performing General Physical Activities to the performance of your current job? (Q16A)
- How important is Handling and Moving Objects to the performance of your current job? (Q17A)
- How important is Controlling Machines and Processes [not computers nor vehicles] to the performance of your current job? (Q18A)

[5] Mongey et al. (2020) propose a variant of the teleworking index in Dingel and Neiman (2020) and a measure of low physical proximity to others at work.
[6] The possible answers for each item are: 1 (never), 2 (once a year or more but not every month), 3 (once a month or more but not every week), 4 (once a week or more but not every day) and 5 (every day).
[7] The possible answers for each item are: 1 (not important), 2 (somewhat important), 3 (important), 4 (Very important) and 5 (extremely important).

- How important is Operating Vehicles, Mechanized Devices, or Equipment to the performance of your current job? (Q20A)
- How important is Performing for or Working Directly with the Public to the performance of your current job? (Q32A)
- How important is Repairing and Maintaining Mechanical Equipment to the performance of your current job? (Q22A)
- How important is Repairing and Maintaining Electronic Equipment to the performance of your current job? (Q23A)
- How important is Inspecting Equipment, Structures, or Materials to the performance of your current job? (Q4A)

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For each question, occupations are classified as “able to work from home” if answers are 1, 2 or 3, and as “cannot be performed at home” if answers are 4 or 5. Finally, occupations are classified as “able to telework” if they are categorised as “able to work from home” in the 15 questions.

A total of 968 occupations of O*NET were categorised as teleworkable or non-teleworkable in this way. We then map O*NET-Standard Occupation Classification (O*NET-SOC2010) to the corresponding US-SOC10 (at the 6-digit level). Next, to obtain results for Europe, we use the ILO crosswalk to translate all US-SOC10 occupations into the EU-LFS occupations (ISCO-08 at the 3-digit level). This mapping between SOC10 and ISCO-08 is far from trivial because it is an unbalanced ‘many-to-many’ match, and correspondence needs to take into account relative weighting of related occupations. For this task, we use the Occupational Employment Statistics (OES) 2018 (which uses US-SOC 10 at the 6-digit level) and has the US employment weights for each occupation. Thus, we can map US-SOC10 occupations in OES (at the 6-digit level) to the ISCO-08 occupations (at the 3-digit level) in EU-LFS, a process which allocates US’s employment across ISCOs in proportion to European employment shares. This mapping of 6-digit SOCs to 3-digit ISCOs (and the corresponding teleworking value for each occupation) is common to all European countries, but the posterior calculation of the weighted teleworking average for each 2-digit ISCO is country-specific, based on the labour weights of the different 3-digit occupations included in each 2-digit code . Finally, we impute the teleworking index based on EU-LFS at the 2-digit ISCO level to each occupation in EU-SILC at the 2-digit ISCO level.

2.3 Teleworking in Europe

In Figure 1 and Table 1 we show the average index of teleworking across Europe. It is observed that teleworking varies significantly across countries: Denmark (0.48), Luxembourg (0.47), Switzerland (0.47) and Norway (0.46) are the countries best prepared for teleworking, while Romania (0.24), Bulgaria (0.28), Slovak Republic (0.31) and Hungary (0.31) show the lowest average teleworking index. It appears therefore that occupational structures in Northern Europe are more prepared for social distancing than in Southern Europe and, especially, than Eastern Europe.

Table 1 shows that the index of teleworking varies significantly not only by countries but also by gender, type of contract (permanent or temporary), type of work (full or part time), and level of education. According to their occupational index of teleworking, women are less affected by social distancing than men in all European countries but the Netherlands, where both sexes have the same capacity to work from home. By type of job, as might be expected, temporary and part-time workers are worse prepared for teleworking than their permanent and full-time counterparts. Only in Austria, Denmark and the UK have temporary workers a higher capacity to telework than permanent workers −implying that, in these countries, temporary contracts are relatively more used in highly teleworkable occupations− while only in Czech Republic, Croatia and Slovak Republic part-time workers are better prepared for working at home than full-time workers.

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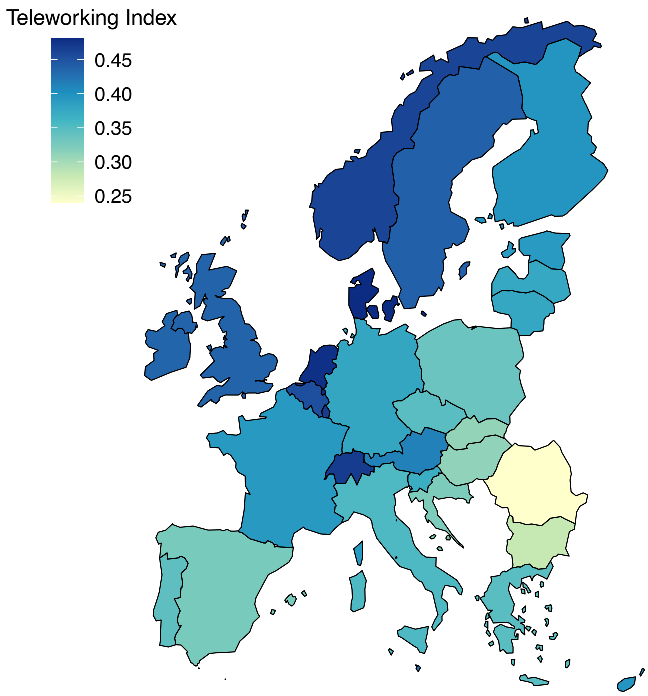
Figure 1. Average index of teleworking across European countries.



Sources: Authors' analysis from O*NET, EU-FLS (2018), and EU-SILC (2018).

Finally, there is a very strong positive relationship between the level of education and the value of teleworking in all European countries. By levels of education, the capacity of working from home for a worker with primary education is highest in Norway (0.33) while for a secondary or tertiary education worker is maximum in Luxembourg (0.43 and 0.72, respectively). This positive relationship between education and teleworking implies that workers with high education, who tend to earn higher salaries, are likely to be less affected by social distancing. However, as governments declare some activities as essential or closed under a lockdown, this outcome might not be straightforward.

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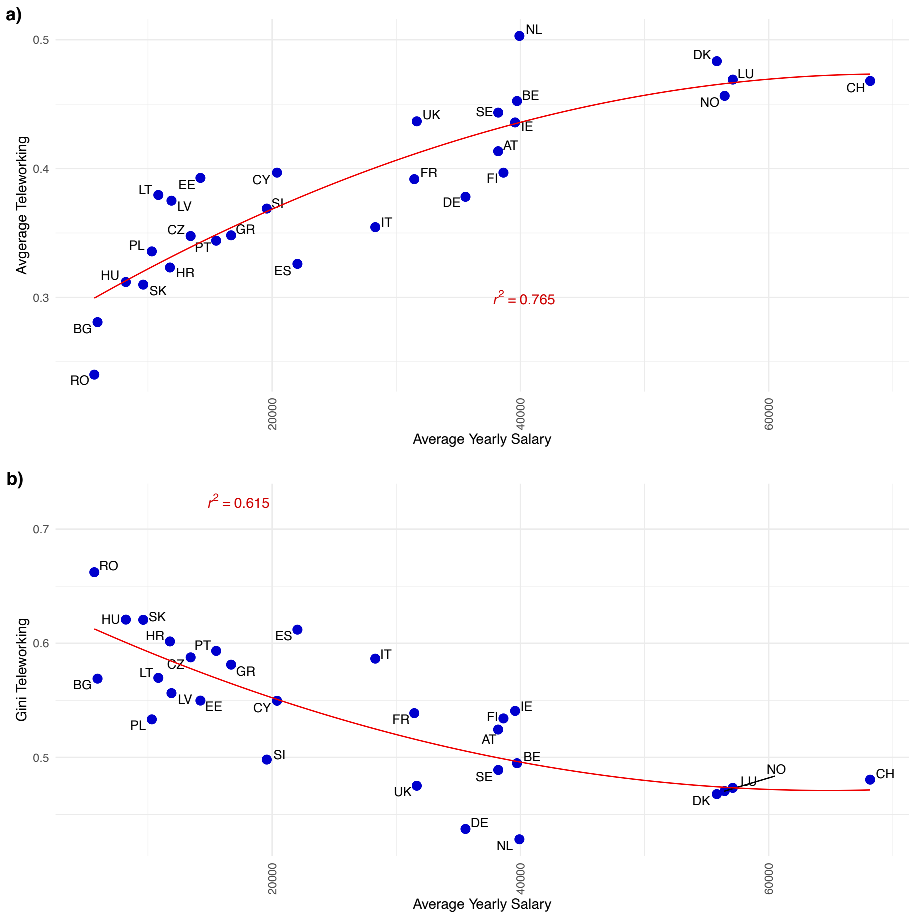
Table 1. The teleworking index in Europe.

Country	Teleworking	Gender		Type		Contract		Education		
		Male	Female	Permanent	Temporary	Full	Part-time	Low	Medium	High
Austria	0.414	0.380	0.454	0.416	0.477	0.415	0.410	0.146	0.322	0.618
Belgium	0.453	0.420	0.490	0.468	0.370	0.473	0.399	0.145	0.297	0.640
Bulgaria	0.281	0.222	0.347	0.282	0.176	0.284	0.211	0.051	0.172	0.585
Switzerland	0.468	0.454	0.485	0.487	0.429	0.478	0.444	0.194	0.411	0.605
Cyprus	0.397	0.319	0.483	0.429	0.272	0.402	0.346	0.082	0.259	0.632
Czech Republic	0.348	0.300	0.407	0.349	0.331	0.345	0.406	0.082	0.253	0.650
Germany	0.378	0.352	0.407	0.379	0.336	0.394	0.338	0.174	0.316	0.571
Denmark	0.481	0.423	0.544	0.488	0.570	0.487	0.432	0.236	0.376	0.643
Estonia	0.391	0.325	0.459	0.381	0.355	0.394	0.364	0.103	0.251	0.596
Spain	0.326	0.292	0.367	0.367	0.222	0.339	0.232	0.096	0.238	0.531
Finland	0.397	0.350	0.446	0.419	0.391	0.407	0.302	0.201	0.236	0.612
France	0.392	0.330	0.458	0.427	0.310	0.403	0.340	0.189	0.274	0.590
Greece	0.348	0.293	0.424	0.450	0.269	0.356	0.264	0.102	0.249	0.594
Croatia	0.322	0.254	0.405	0.342	0.216	0.322	0.334	0.066	0.215	0.660
Hungary	0.312	0.233	0.400	0.329	0.199	0.317	0.230	0.083	0.189	0.677
Ireland	0.436	0.396	0.484	0.455	0.313	0.474	0.311	0.192	0.310	0.563
Italy	0.355	0.302	0.427	0.376	0.249	0.361	0.318	0.139	0.365	0.613
Lithuania	0.377	0.310	0.443	0.383	0.232	0.382	0.310	0.085	0.168	0.645
Luxembourg	0.469	0.447	0.497	0.482	0.343	0.483	0.402	0.172	0.435	0.718
Latvia	0.375	0.307	0.439	0.369	0.196	0.377	0.357	0.096	0.221	0.641
Netherlands	0.478	0.479	0.477	0.510	0.448	0.506	0.443	0.234	0.362	0.663
Norway	0.462	0.425	0.502	0.471	0.421	0.471	0.390	0.328	0.369	0.607
Poland	0.336	0.264	0.419	0.384	0.243	0.339	0.289	0.079	0.180	0.637
Portugal	0.344	0.292	0.397	0.362	0.296	0.350	0.241	0.142	0.368	0.654
Romania	0.240	0.194	0.306	0.276	0.160	0.253	0.079	0.078	0.127	0.687
Sweden	0.439	0.390	0.494	0.459	0.383	0.454	0.376	0.219	0.356	0.630
Slovenia	0.369	0.308	0.440	0.383	0.311	0.371	0.327	0.064	0.221	0.656
Slovak Republic	0.310	0.242	0.389	0.317	0.232	0.310	0.325	0.083	0.204	0.645
United Kingdom	0.437	0.414	0.462	0.452	0.460	0.465	0.363	0.226	0.324	0.572
Europe	0.380	0.337	0.429	0.393	0.293	0.387	0.346	0.148	0.282	0.599

To end the description of our teleworking index across Europe, we estimate now the correlation between teleworking and the average salary by countries. In Figure 2 (panel a) we observe that the average of teleworking in a country is positively correlated with the average annual salary in that country. Likewise, inequality of teleworking (Gini coefficient) is negatively associated with average annual salary (Figure 2, panel b). Therefore, European countries with higher average salaries seem to be potentially less sensitive to social distancing measures. Again, the existence of activities that are essential or closed under the lockdown will make us arrive at more nuanced findings in terms of the estimated effect on wage inequality, as we will see.

Figure 2. Teleworking and average salaries in Europe.



Sources: Authors' analysis from O*NET, EU-FLS (2018), and EU-SILC (2018).

3. Methodology

Teleworking capacity is not the only determinant of workers ability to effectively work and keep their wage during the lockdown period. We need to take into account that some occupations are not affected by the lockdown because they are considered essential −like healthcare or agriculture− while others are fully closed to contain the spread of Covid-19,

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like accommodation or entertainment. Based on the decisions made by the governments in Italy (Gazzetta Ufficiale della Repubblica Italiana, 23rd February and 25th March, 2020) and Spain (Boletín Oficial del Estado, 14th March and 29th March, 2020), thus far, two of the most affected countries by the pandemic in the world, we have defined the essential and closed occupations at the ISCO-08 2-digit level and NACE (Rev.2) 1-digit level (see the details in Appendix B).[8]

Thus, occupations in "Agriculture, forestry and fishing", "Public administration and defense", and "Human health and social work" are considered entirely essential, while "Transportation and storage", "Information and communication", and "Financial and insurance services" are classified as partially essential. On the other hand, "Wholesale and retail trade", "Accommodation and food service activities", "Arts, entertainment and recreation", "Other service activities", and "Activities of households" as Employers are assumed to be closed. In Appendix B (Tables B3-B7) we give a detailed description of our classification of essential and closed occupations by industries.

Having calculated the teleworking index and identified the essential and closed occupations, we construct the Lockdown Working Ability (LWA) index. This measure summarizes the capacity of individuals to work under a lockdown taking into account not only the value of their occupation's teleworking index, but also if such occupation is essential (e) or closed (c). The key idea is that essential workers can work during the lockdown (to the extent that their occupation is essential) regardless whether the occupation can be teleworked or not. On the contrary, workers in closed activities cannot work at all to the extent that their overall activity has been closed. In all remaining cases, working capacity will depend on the share of that occupation that can be teleworked.

Formally, the first step in constructing the LWA index requires to split the population of n workers into three groups according to the occupation o_i of each worker $i \in \{1, 2, \dots, n\}$. If the individual has an occupation that is neither essential nor closed, the value of her LWA_i index will be equal to the value of her index of teleworking, $T_i \in [0,1]$.

[8] Given the level of disaggregation available in EU-SILC for some particular countries, we have defined essential and closed occupations at the ISCO-08 1-digit level and NACE (Rev.2) 1-digit level for Bulgaria, Slovenia and Poland (see Tables B5 and B6 in Appendix B), and only at the ISCO-08 2-digit level for Denmark (see Table B7 in Appendix B).

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If the person has an essential job ($o_i = e$), we will compute the LWA index as $LWA_i = E_i + (1 - E_i)T_i$, where $E_i \in (0,1]$ is the essentiality score given to the occupation of the individual. Thus, for partially essential occupations ($E_i < 1$), the non-essential share of the occupation $(1 - E_i)$ can work during lockdown only to the extent that it is teleworkable. Finally, if the person has a job that is closed ($o_i = c$), we will calculate the LWA index as $LWA_i = (1 - C_i)T_i$, where $C_i \in (0,1]$ is the value given to the closed occupation of the individual. In partially closed occupations ($C_i < 1$), the non-closed share of the occupation $(1 - C_i)$ can work to the extend that is teleworkable. In summary, the Lockdown Working Ability index is calculated as follows:

$$LWA_i = \begin{cases} E_i + (1 - E_i)T_i & o_i = e \\ (1 - C_i)T_i & o_i = c \\ T_i & o_i \neq e, c \end{cases}, \qquad (1)$$

for all $i \in \{1, 2, \dots, n\}$.

In Section 2 we showed that the average of teleworking in a country is strongly correlated with the average annual salary of that country. Thus, we argued that, in principle, workers from countries with high average salaries would be less affected by social distancing hinting a potential increase in inequality. However, when we consider the essentiality status of some occupations and the closure of some others under a lockdown, the above correlation vanishes. As we show in Figure 3 (panel a), the correlation between the LWA index and the average annual salary in a country is positive but very small (see the large dispersion of points around the fitted curve). In the same manner, the correlation between the inequality of the LWA index (according to the Gini) and the average annual salary in a country is negative but again very small (Figure 3, panel b). Once essential and closed occupations are considered, the changes in wage inequality caused by the lockdown are difficult to foresee.

The next step is to calculate the potential wage loss due to the lockdown for every individual in the population. We adopt six possible scenarios. In the first three cases we assume three different temporal lengths for the lockdown: *i*) one month; *ii*) two months;

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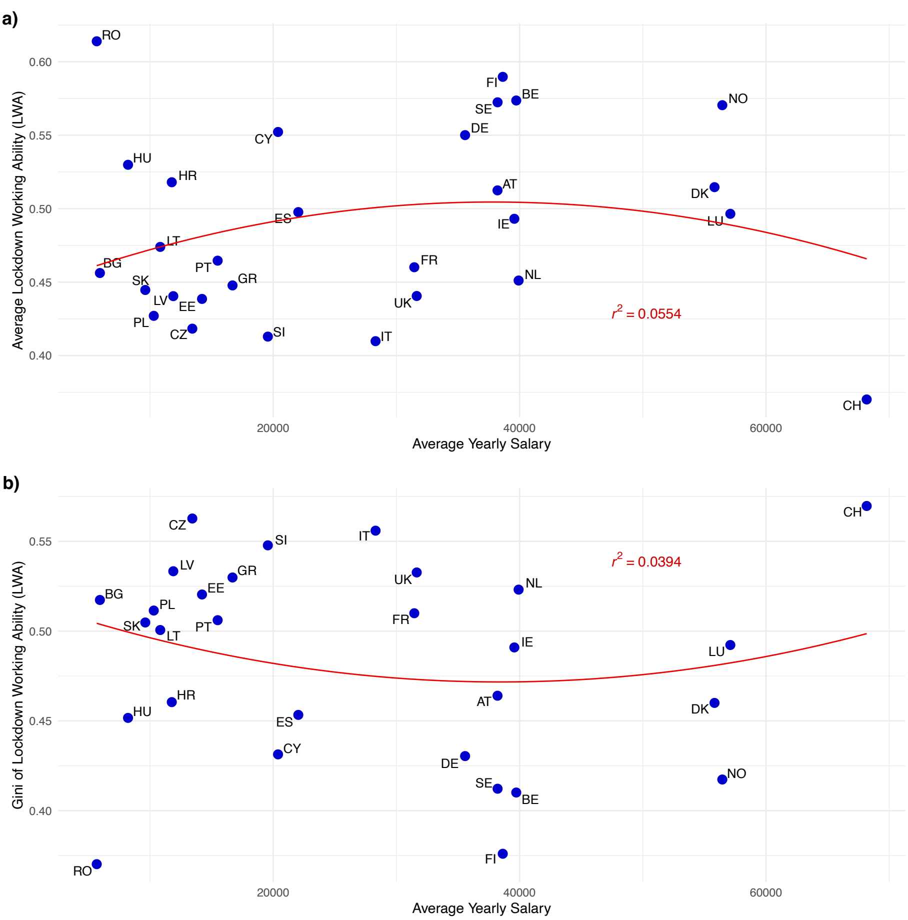
and *iii*) four months. In the remaining three cases we add to *i*, *ii*, and *iii* an additional period of six months during which closed occupations can be developed only at 80% of full capacity. The idea behind these last three scenarios is that governments may not allow a fully functioning of closed occupations after the lockdown to avoid a new outbreak of the virus. We simulate the same six scenarios for all European countries so differences across countries are due to their distinct productive structures. Thus, we isolate our analysis from other potential causes like the particular mitigation measures adopted by each European government.

Figure 3. Lockdown Working Ability (LWA) and average salaries in Europe.



Sources: Authors' analysis from O*NET, EU-FLS (2018), and EU-SILC (2018).

Using the LWA index, we calculate the wage loss (wl) experienced by every individual during the lockdown according to the six simulated scenarios described. For the cases *i*, *ii*, and *iii* the equation we estimate is the following:

$$wl_{it} = w_{it-1} \cdot D_t(1 - LWA_i), \quad (2)$$

where w_{it-1} is the annual wage of individual i in period $t-1$ (before the lockdown) and D_t represents the duration of the lockdown in annual terms, i.e., $D_t = \frac{1}{12}$ for one month, $D_t = \frac{2}{12}$ for two months, and $D_t = \frac{4}{12}$ for four months.

For the cases *iv*, *v*, and *vi* we apply the same equation (2) unless the individual has a closed occupation, in which case, we need to additionally consider the wage loss due to the imposed partial functioning of 80% of their occupation (20% closure) for six additional months. The relevant equation for scenarios *iv*, *v*, and *vi* is:

$$wl_{it} = w_{it-1}\left[D_t \cdot (1 - LWA_i) + 1_c \cdot \frac{6}{12} \cdot 0.2\right], \quad (3)$$

where $1_c = \begin{cases} 1 & if\ o_i = c \\ 0 & if\ o_i \neq c \end{cases}$ is the indicator function.

The estimated wage loss of each individual in the population will allow us to analyse the changes in poverty and inequality across Europe under the lockdown. A first view of these changes between dates $t-1$ (pre-lockdown) and t can be achieved by representing the loss rate (l) in the wage of every worker caused by the lockdown, i.e., $l_{it} = \frac{w_{it} - w_{it-1}}{w_{it-1}} = \frac{wl_{it}}{w_{it-1}}$, since $w_{it} = w_{it-1} - wl_{it}$. For this task we first order the workers by their pre-lockdown wage w_{it-1} and group them into centiles (q), obtaining the mean loss rate l_{qt} at each centile. The result is the Lockdown Incidence Curve (LIC) where it is easy to appreciate which part of the wage distribution (low, middle, high) suffers the largest

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relative wage losses.[9] It can be proved that if l_{qt} is an increasing (decreasing) function for all q then inequality falls (rises) with the lockdown for all inequality measures satisfying the Pigou–Dalton transfer principle.[10]

Closely related to the LIC we have the mean loss rate for the poor.[11] Let $H(z)$ denote the headcount index defined as the proportion of workers whose salary is less than z, where z is the poverty line (60% of the median wage in our case). Then, the mean loss rate for the poor (P) is defined as the area under the LIC up to the headcount index divided by the headcount measure and it can be expressed as:

$$P = \frac{1}{H(z)} \sum_{q=1}^{H(z)} l_q. \tag{4}$$

When $l_q < 0$ for all $q < H(z)$ one can conclude that the lockdown was poverty augmenting. For the analysis of poverty, we will represent the LICs for the set of European countries and compute the P index and the relative change in $H(z)$ for the six scenarios of lockdown. To calculate the absolute change in $H(z)$, $\Delta^A H(z) = H_t(z) - H_{t-1}(z)$, we maintain constant the poverty line z before the lockdown.

After gaining some understanding about the changes in poverty caused by the lockdown, we estimate the changes in wage inequality. Of all the possible inequality indices that fulfill the basic principles found in the literature on inequality (progressive transfers, symmetry, scale invariance and replication of the population) we adopt the Gini coefficient (G) and the MLD index. The first measure is the most popular index of inequality and can be expressed as follows:

[9] This curve is an adaptation to our framework of the Growth Incidence Curve (GIC) proposed in Ravallion and Chen (2003). For a view on the literature that studies the capacity of economic growth to reduce poverty see also Kakwani and Pernia (2000), Kakwani and Son (2008) and Duclos (2009), among others.
[10] This result comes from well-known results on tax progressivity and inequality. See, for example, Eichhorn et al. (1984).
[11] This measure is an adaption to our context of the mean growth rate for the poor proposed in Ravallion and Chen (2003). It is equivalent to the rate of change in the Watts index of poverty (Watts, 1968) normalized by the headcount index. Zheng (1993) identifies a large set of axioms for which the Watts index emerges as the unique poverty measure.

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$$G(w) = \frac{1}{2n^2\mu}\sum_{i=1}^{n}\sum_{j=1}^{n}\left|w_i - w_j\right| \quad (5)$$

where w represents the wage distribution, w_i is the salary of individual i, and μ is the mean wage of the economy. Absolute changes in wage inequality are measured as the difference $\Delta^A G = G(w_t) - G(w_{t-1})$, where w_{t-1} is the pre-lockdown wage distribution and w_t is the wage distribution under a given scenario (cases *i-vi*). Meanwhile, relative changes in wage inequality are measured as percentages of pre-lockdown inequality, i.e., $\Delta^R G = \frac{G(w_t)-G(w_{t-1})}{G(w_{t-1})} \times 100$.

Unfortunately, the broadly used Gini index is not additively decomposable into a between-group component and a within-group component. Its decomposition includes also a residual term which cannot be assigned to the between-group or the within-group component. For this reason, we use the MLD index in the last part of our analysis, where we decompose the overall estimated change of inequality in Europe into its between-countries and within-countries components. The MLD belongs to the Generalized Entropy class which is the only class of inequality indices that is additively decomposable into a between-group and a within-group component (Bourguignon, 1979 and Shorrocks, 1980). Moreover, the MLD has a path-independent decomposition, so the result of the decomposition is independent of which component (between-group or within-group) is eliminated first (Foster and Shneyerov, 2000). In addition, the MLD is the only measure that respects both the principle of transfers -the cornerstone of the literature on inequality measurement- and the principle of monotonicity in distance (Cowell and Flachaire, 2018).[12] The MLD (T) is defined as:

[12] Some standard inequality measures like the Gini coefficient can be written as ratios, where the denominator is the mean (see equation (4)). As a result, when earnings move away from equality, both the numerator and denominator can change in the same direction and such inequality measures may decrease (instead of increase) in some cases. This undesirable behaviour is not shared by inequality indices whose denominator is the median. Unfortunately, these indices do not fulfil the principle of transfers, only the MLD satisfies both principles, transfers and monotonicity in distance, simultaneously.

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$$T(w) = \frac{1}{n}\sum_{i=1}^{n} ln\left(\frac{\mu}{w_i}\right). \quad (6)$$

Absolute and relative changes in wage inequality measured by the MLD index will be denoted by $\Delta^A T = T(w_t) - T(w_{t-1})$ and $\Delta^R T = \frac{T(w_t)-T(w_{t-1})}{T(w_{t-1})} \times 100$, respectively.

Now, let $w = (w^1, \ldots, w^M)$ be a partition of wage into M groups (countries), μ_m the mean of the wage distribution w^m and n_m the population size associated with the wage distribution w^m, where $n = \sum_{m=1}^{M} n_m$. Then, taking advantage of the additive decomposability property of the MLD and grouping workers by countries, the MLD index can be exactly decomposed as follows:

$$T(w) = T(\mu_1 1^{n_1}, \mu_2 1^{n_2}, \ldots, \mu_m 1^{n_m}) + \sum_{m=1}^{M} \frac{n_m}{n} T(w^m), \quad (7)$$

where 1^n is n-coordinated vector of ones. Expression (6) provides a breakdown of overall wage inequality into between-group and within-group terms. The between-group component $T(\mu_1 1^{n_1}, \mu_2 1^{n_2}, \ldots, \mu_m 1^{n_m})$ is the level of wage inequality that would arise if each worker in a country enjoys the mean wage of the country, and the within-group component $\sum_{m=1}^{M} \frac{n_m}{n} T(w^m)$ is the weighted sum of wage inequalities within different countries. In this manner, the two components of overall wage inequality can be disentangled in our analysis.

4. Inequality changes in Europe

How large are the wage losses experienced by workers during the lockdown? In which part of the wage distribution will the highest wage losses take place? To give an answer to these questions we have calculated the LIC for the set of European countries and simulation cases. In Figure 4 we represent the LICs for a subset of countries under two

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months of lockdown (case *iii*).[13] First, we show the LIC for three countries, Romania, Poland and Slovakia, where the main wage losses take place at the upper part of the wage distribution (Figure 4, panel a). Second, we represent the LIC for Norway and Greece, two countries where wage losses are distributed quite equally across percentiles (Figure 4, panel b). In the third graph we show the two countries in Europe where wage losses are more concentrated at the bottom of the wage distribution, Cyprus and Ireland (Figure 4, panel c). Finally, we highlight the LIC for Germany, the UK and France (Figure 4, panel d). In this case, wage losses tend to decrease monotonically with the percentile that the worker occupies.

The first relevant thing that we observe in Figure 4 (panels a-d) is that wage losses are sizeable. In fact, in some countries the wage losses at a given percentile can be superior to 10%, see for example, the case of workers at the 75th percentile of the wage distribution in Romania, Slovakia and Poland, and of workers at the 25th percentile in Cyprus and Ireland. Secondly, in general, wage losses are not equally distributed along the wage distribution since they vary significantly with the centile and the country of the workers. This result can be observed by simply comparing the LICs represented in Figure 4. Third, there is no straightforward relationship between the average wage of a country and its distribution of wage losses caused by the lockdown. For example, we observe that the distribution of wage losses is similar for Norway and Greece, and Ireland and Cyprus, despite that these countries have significantly different average wages. The distribution of wage losses is similar when other scenarios of simulation (not shown here) are considered, and the main difference lies only in the size of the wage drop. As the lockdown period gets longer, and when the partial closure of some activities is considered, wage losses get bigger.

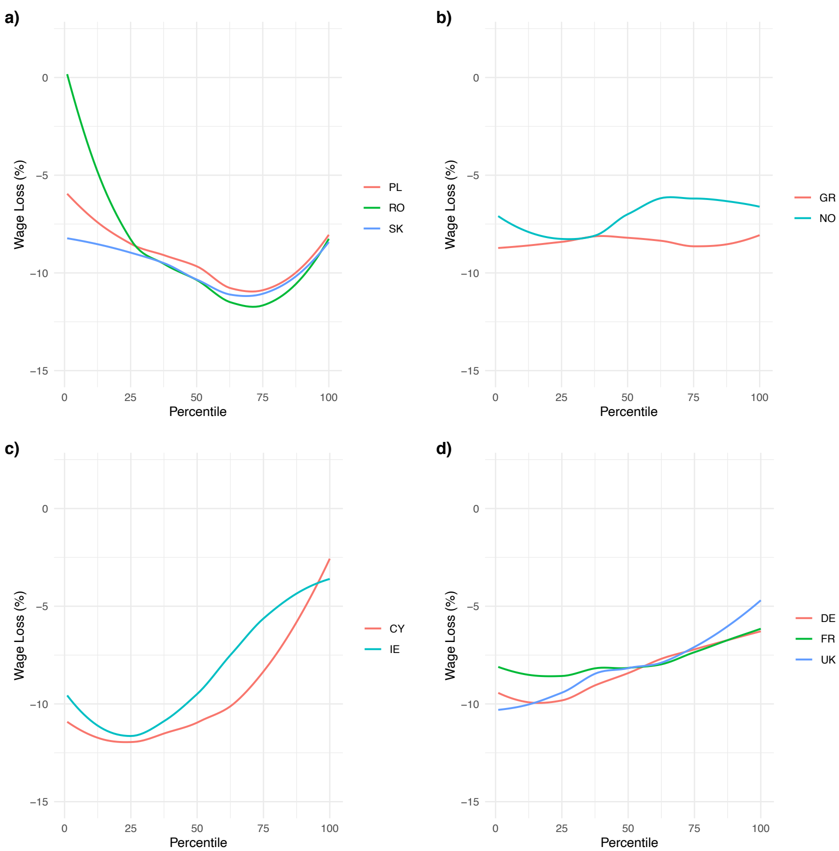
4.1 Changes in poverty due to enforced social distancing

Let us estimate the change in poverty in a formal way by computing the mean loss rate for the poor P. In Table 2 (columns 2-7) we show this measure for the six simulations under consideration. It is observed that the lockdown is poverty augmenting in all

[13] Lockdown Incidence Curves have been smoothed using local polynomial regression with span 0.75 and degree 2.

simulated cases for all European countries. For example, under a lockdown of two months, we find a mean loss rate for the poor equal to 10.3% for Europe as a whole. If we also consider a 6-month period of partial functioning of closed activities (scenario *v*), the mean loss rate for the poor in Europe increases up to 22.3%. By countries, the mean loss rates reported in Table 2 are also sizeable and consistent with what the LICs distribution pointed at. Thus, regardless the simulation scenario undertaken, the highest loss for the poor is found in Cyprus (for example, 12.2% for case *ii*), while the smallest one happens in Romania (3.1% for case *ii*). The complete ordering of European countries according to the mean loss rate for the poor under a lockdown of 2 months is shown in Figure 5.

Figure 4. Lockdown Incidence Curves in Europe (scenario *ii*).



Sources: Authors' analysis from O*NET, EU-FLS (2018), and EU-SILC (2018).

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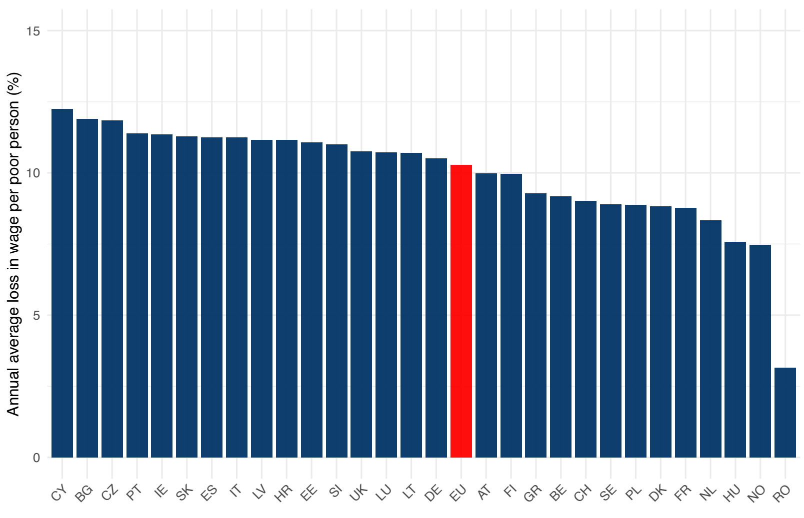
Despite that the headcount index is not necessarily consistent with the LIC (see Essama-Nssah and Lambert, 2009), we also calculate the absolute change of this index. In Table 2 (columns 8-20) we present the results for the headcount index under the six simulated scenarios. Again, poverty increases for all simulated cases and all European countries. Also, changes in poverty according to the headcount index are important. For example, in Europe as a whole, this measure increases 3 percentage points under two months of lockdown and 10 percentage points if we consider an additional period of six months during which closed activities are partially functioning at 80%. These values imply that −in absence of compensating policies− the percentage of poor people in Europe may substantially increase even if lockdown does not last long. By countries, we find that the highest increase in poverty according to the headcount index is found in Croatia (cases *i*, *ii*, *iii*, *iv*, *vi*) and Cyprus (cases *v*). On the contrary, the smallest percentage increase in poverty according to the headcount index happens in Romania (case *i*), Switzerland (case *ii*), the Netherlands (case *iii*) and Denmark (cases *iv*, *v* and *vi*).

Figure 5. Mean loss rates for the poor in Europe (scenario *ii*).



Sources: Authors' analysis from O*NET, EU-FLS (2018), and EU-SILC (2018).

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4.2 Inequality changes in Europe

Now, we calculate the absolute and relative changes in wage inequality caused by the lockdown, but first we comment on initial wage inequality (baseline) across Europe (Tables 3 and 4). The ordering of European countries according to their initial wage inequality is similar for both the Gini and the MLD indices. Thus, Slovakia is clearly the European country with the lowest pre-lockdown wage inequality. Other countries with low levels of wage inequality before the lockdown are Sweden, Czechia, Belgium and Norway, all of them with a Gini index below 0.30. On the other extreme of the spectrum, we find the countries with the highest level of pre-lockdown wage inequality: Bulgaria, Ireland, the UK and Spain, all of them with a Gini index above 0.40.

When comparing wage inequality after the lockdown with the baseline, it is observed that changes in inequality are sizeable and increase in all countries with the duration of the lockdown and the partial closure of some activities regardless the inequality index under consideration (Tables 3 and 4). According to the Gini coefficient, increase at scenario *ii* ranges from 2.2% (the Netherlands) to 4.9% (Cyprus). At the more extreme scenario *v* the Gini inequality increases range from 9.5% (Denmark) to 21.2% (Slovakia). Cyprus shows the greatest increase in inequality in cases *i*, *ii* and *iv*, while Slovakia does in cases *iii*, *v* and *vi*. At the other end Norway (scenario *i*), the Netherlands (scenarios *ii* and *iii*), Denmark (scenarios *iv* and *v*) and Germany (scenario *vi*) present the lowest values.

The relative changes can be partly determined by the initial level of inequality (Slovakia has the lowest baseline wage inequality) and a scrutiny of the absolute changes in the Gini coefficient reveals that Cyprus is the European country where inequality increases the most in absolute terms for all simulation cases. For example, at our scenario *ii* Cyprus shows an increase of 1.9 Gini points (in percentage). On the other hand, the smallest absolute change in inequality is found in Norway (scenarios *i* and *ii*), the Netherlands (scenarios *iii* and *vi*) and Denmark (scenarios *iv* and *v*). For scenario *ii*, Norway shows an absolute inequality increase of 0.7 Gini points (in percentage).

The MLD index –as can be expected– is in general more sensitive to the simulated wage losses in our lockdown scenarios, showing higher relative changes in inequality than Gini in all countries. Czechia experiences the highest absolute change in wage inequality for

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cases *i*, *ii* and *iii*, and Croatia for the other three cases. About relative changes in inequality, Slovakia -which has high absolute changes and the lowest baseline MLD index- shows the largest values for all the simulation scenarios. Finally, Romania has the smallest increase in absolute and relative wage inequality for all cases.

Our findings show an increase in inequality for all European countries but, would inequality changes be different enough to increase inequality between countries? The short answer is yes; the long answer is yes, but much less than the inequality changes occurring within countries. In Table 5 we show the results of the decomposition of wage inequality for all European workers.

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Table 2. Poverty changes in Europe.

	Mean Loss Rate for the Poor (P)						Headcount Index (H)												
Country	**P 1m**	**P 2m**	**P 4m**	**P 1m+CL**	**P 2m+CL**	**P 4m+CL**	**H**	**H 1m**	**Δ^AH**	**H 2m**	**Δ^AH**	**H 4m**	**Δ^AH**	**H 1m+CL**	**Δ^AH**	**H 2m+CL**	**Δ^AH**	**H 4m+CL**	**Δ^AH**
Austria	5.0	10.0	20.0	18.8	23.8	33.8	0.250	0.269	0.019	0.290	0.040	0.349	0.098	0.339	0.088	0.360	0.109	0.418	0.168
Belgium	4.6	9.2	18.3	15.2	19.8	29.0	0.177	0.193	0.016	0.216	0.039	0.278	0.101	0.275	0.098	0.305	0.128	0.360	0.183
Bulgaria	5.9	11.9	23.8	18.2	24.1	36.0	0.230	0.250	0.021	0.283	0.053	0.370	0.141	0.342	0.113	0.387	0.157	0.478	0.249
Switzerland	4.5	9.0	18.0	18.1	22.7	31.7	0.254	0.265	0.011	0.279	0.026	0.335	0.082	0.339	0.086	0.364	0.111	0.412	0.158
Cyprus	6.1	12.2	24.5	26.3	32.4	44.7	0.217	0.243	0.026	0.278	0.062	0.370	0.153	0.386	0.170	0.430	0.214	0.505	0.288
Czechia	5.9	11.8	23.7	19.4	25.3	37.2	0.153	0.182	0.029	0.209	0.056	0.309	0.156	0.266	0.112	0.300	0.146	0.388	0.234
Germany	5.3	10.5	21.0	19.4	24.6	35.1	0.271	0.288	0.016	0.309	0.037	0.359	0.088	0.348	0.077	0.375	0.103	0.421	0.150
Denmark	4.4	8.8	17.6	12.1	16.5	25.3	0.155	0.169	0.014	0.184	0.029	0.242	0.087	0.202	0.047	0.227	0.072	0.291	0.135
Estonia	5.5	11.1	22.1	17.9	23.4	34.5	0.237	0.262	0.024	0.288	0.051	0.355	0.118	0.334	0.097	0.366	0.129	0.440	0.203
Spain	5.6	11.2	22.5	21.6	27.2	38.5	0.259	0.280	0.022	0.310	0.051	0.375	0.116	0.378	0.119	0.413	0.154	0.476	0.217
Finland	5.0	10.0	19.9	17.3	22.3	32.3	0.177	0.194	0.017	0.216	0.040	0.292	0.116	0.286	0.109	0.319	0.142	0.382	0.205
France	4.4	8.8	17.5	14.6	19.0	27.7	0.202	0.214	0.013	0.236	0.035	0.311	0.110	0.306	0.104	0.336	0.135	0.398	0.197
Greece	4.6	9.3	18.6	20.2	24.8	34.1	0.228	0.255	0.026	0.279	0.050	0.349	0.121	0.366	0.137	0.408	0.179	0.486	0.258
Croatia	5.6	11.2	22.3	18.9	24.4	35.6	0.153	0.196	0.043	0.238	0.085	0.356	0.203	0.323	0.170	0.365	0.212	0.468	0.315
Hungary	3.8	7.6	15.1	12.4	16.1	23.7	0.155	0.170	0.015	0.195	0.041	0.302	0.147	0.262	0.108	0.304	0.149	0.390	0.235
Ireland	5.7	11.4	22.7	22.8	28.4	39.8	0.268	0.293	0.026	0.316	0.048	0.381	0.114	0.375	0.107	0.401	0.134	0.457	0.190
Italy	5.6	11.2	22.5	22.3	28.0	39.2	0.225	0.244	0.019	0.269	0.044	0.345	0.120	0.341	0.115	0.376	0.151	0.447	0.221
Lithuania	5.4	10.7	21.4	17.4	22.8	33.5	0.229	0.267	0.037	0.302	0.073	0.373	0.144	0.349	0.120	0.387	0.158	0.461	0.231
Luxembourg	5.4	10.7	21.4	19.0	24.3	35.0	0.215	0.243	0.028	0.283	0.068	0.355	0.140	0.317	0.102	0.343	0.128	0.406	0.191
Latvia	5.6	11.2	22.3	18.5	24.1	35.3	0.226	0.256	0.030	0.286	0.060	0.362	0.136	0.332	0.106	0.367	0.142	0.442	0.216
Netherlands	4.2	8.3	16.6	16.5	20.7	29.0	0.242	0.257	0.015	0.276	0.035	0.322	0.080	0.326	0.084	0.348	0.107	0.396	0.155
Norway	3.7	7.5	14.9	11.9	15.6	23.1	0.178	0.195	0.018	0.221	0.044	0.289	0.111	0.290	0.112	0.321	0.143	0.382	0.204
Polonia	4.4	8.9	17.7	14.8	19.2	28.1	0.147	0.180	0.033	0.227	0.080	0.323	0.177	0.275	0.128	0.323	0.177	0.407	0.260
Portugal	5.7	11.4	22.8	19.9	25.6	37.0	0.128	0.147	0.019	0.178	0.049	0.303	0.174	0.267	0.139	0.303	0.174	0.412	0.284
Romania	1.6	3.1	6.3	3.5	5.1	8.2	0.193	0.201	0.008	0.221	0.028	0.346	0.153	0.309	0.115	0.357	0.164	0.472	0.279
Sweden	4.4	8.9	17.8	15.2	19.6	28.5	0.186	0.201	0.015	0.220	0.034	0.283	0.097	0.286	0.100	0.318	0.132	0.381	0.195
Slovenia	5.5	11.0	22.0	16.7	22.2	33.2	0.181	0.201	0.020	0.238	0.057	0.344	0.163	0.297	0.116	0.333	0.152	0.420	0.239
Slovakia	5.6	11.3	22.6	17.7	23.4	34.6	0.117	0.141	0.024	0.180	0.063	0.283	0.166	0.252	0.135	0.307	0.190	0.404	0.287
UK	5.4	10.8	21.5	20.2	25.5	36.3	0.259	0.277	0.018	0.296	0.037	0.352	0.092	0.349	0.090	0.378	0.119	0.432	0.173
Europe	5.1	10.3	20.6	17.2	22.3	32.6	0.321	0.336	0.015	0.352	0.031	0.395	0.073	0.393	0.072	0.419	0.098	0.471	0.150

Note: P is the mean loss rate for the poor and H is the headcount index. CL is partial closure, while 1m, 2m and 3m refer to 1 month, 2 months and 3 months, respectively. Δ^AH is the change in the headcount index.

Table 3. Wage inequality changes in Europe (Gini).

Country	Baseline	G 1m	$\Delta^A G$	$\Delta^R G$	G 2m	$\Delta^A G$	$\Delta^R G$	G 4m	$\Delta^A G$	$\Delta^R G$	G 1m+CL	$\Delta^A G$	$\Delta^R G$	G 2m+CL	$\Delta^A G$	$\Delta^R G$	G 4m+CL	$\Delta^A G$	$\Delta^R G$
Austria	0.388	0.393	0.005	1.4	0.400	0.012	3.2	0.420	0.032	8.2	0.422	0.033	8.6	0.434	0.046	11.8	0.467	0.079	20.4
Belgium	0.296	0.300	0.004	1.4	0.306	0.010	3.5	0.325	0.029	9.9	0.326	0.030	10.2	0.339	0.043	14.5	0.373	0.078	26.3
Bulgaria	0.442	0.449	0.006	1.4	0.456	0.014	3.2	0.477	0.035	7.8	0.480	0.038	8.6	0.495	0.052	11.9	0.534	0.092	20.7
Switzerland	0.370	0.374	0.004	1.1	0.380	0.010	2.6	0.397	0.027	7.2	0.400	0.030	8.1	0.412	0.042	11.4	0.446	0.075	20.3
Cyprus	0.388	0.397	0.009	2.2	0.407	0.019	4.9	0.434	0.046	11.9	0.447	0.058	15.0	0.466	0.078	20.0	0.516	0.128	32.9
Czechia	0.296	0.302	0.006	2.1	0.310	0.014	4.8	0.333	0.038	12.8	0.329	0.033	11.2	0.343	0.047	16.0	0.383	0.088	29.7
Germany	0.391	0.396	0.004	1.1	0.401	0.010	2.6	0.417	0.026	6.7	0.423	0.032	8.2	0.434	0.043	10.9	0.463	0.071	18.2
Denmark	0.304	0.310	0.005	1.7	0.317	0.012	4.0	0.337	0.033	10.7	0.323	0.019	6.2	0.333	0.029	9.5	0.361	0.056	18.4
Estonia	0.362	0.367	0.005	1.4	0.373	0.011	3.1	0.393	0.031	8.4	0.395	0.033	9.2	0.408	0.046	12.8	0.445	0.083	22.8
Spain	0.405	0.412	0.007	1.6	0.420	0.015	3.7	0.442	0.037	9.1	0.448	0.042	10.5	0.463	0.057	14.1	0.502	0.096	23.8
Finland	0.318	0.323	0.005	1.4	0.329	0.011	3.5	0.349	0.031	9.7	0.350	0.031	9.8	0.363	0.045	14.0	0.400	0.082	25.7
France	0.365	0.368	0.003	1.0	0.373	0.009	2.3	0.390	0.025	6.8	0.389	0.025	6.8	0.401	0.036	9.9	0.433	0.069	18.8
Greece	0.368	0.372	0.004	1.2	0.379	0.011	2.9	0.397	0.029	8.0	0.409	0.041	11.1	0.424	0.056	15.2	0.465	0.097	26.4
Croatia	0.322	0.328	0.007	2.0	0.337	0.015	4.7	0.361	0.039	12.2	0.368	0.046	14.3	0.385	0.063	19.6	0.431	0.109	34.0
Hungary	0.346	0.350	0.004	1.2	0.356	0.010	2.9	0.375	0.029	8.3	0.374	0.028	8.0	0.386	0.040	11.5	0.420	0.074	21.4
Ireland	0.430	0.437	0.007	1.7	0.446	0.016	3.8	0.469	0.039	9.0	0.472	0.042	9.9	0.487	0.057	13.2	0.523	0.094	21.8
Italy	0.377	0.382	0.005	1.5	0.389	0.013	3.4	0.410	0.033	8.9	0.415	0.039	10.2	0.429	0.053	14.0	0.469	0.092	24.5
Lithuania	0.400	0.406	0.006	1.5	0.413	0.013	3.4	0.434	0.034	8.6	0.431	0.032	7.9	0.445	0.046	11.5	0.485	0.085	21.3
Luxembourg	0.390	0.398	0.008	2.0	0.407	0.017	4.3	0.429	0.039	9.9	0.427	0.036	9.3	0.440	0.050	12.8	0.474	0.084	21.5
Latvia	0.383	0.390	0.007	1.8	0.399	0.015	4.0	0.421	0.038	9.9	0.420	0.037	9.6	0.435	0.051	13.4	0.473	0.090	23.4
Netherlands	0.366	0.369	0.003	0.9	0.374	0.008	2.2	0.388	0.022	6.1	0.393	0.028	7.6	0.404	0.038	10.5	0.433	0.067	18.4
Norway	0.300	0.302	0.003	0.8	0.307	0.007	2.3	0.322	0.023	7.6	0.330	0.030	10.0	0.341	0.042	13.9	0.375	0.075	25.1
Polonia	0.333	0.338	0.005	1.5	0.345	0.012	3.6	0.365	0.032	9.5	0.371	0.038	11.5	0.385	0.052	15.6	0.423	0.090	26.9
Portugal	0.395	0.403	0.008	2.0	0.413	0.017	4.4	0.438	0.043	10.8	0.436	0.040	10.2	0.452	0.057	14.4	0.495	0.099	25.1
Romania	0.343	0.347	0.005	1.4	0.354	0.012	3.4	0.374	0.032	9.3	0.372	0.030	8.7	0.387	0.044	12.9	0.428	0.085	25.0
Sweden	0.289	0.294	0.004	1.4	0.300	0.010	3.6	0.320	0.031	10.7	0.322	0.033	11.2	0.336	0.046	15.9	0.373	0.084	29.0
Slovenia	0.328	0.335	0.007	2.1	0.343	0.015	4.7	0.366	0.039	11.8	0.363	0.035	10.8	0.378	0.050	15.3	0.418	0.090	27.5
Slovakia	0.254	0.259	0.005	1.8	0.266	0.012	4.6	0.289	0.035	13.7	0.292	0.038	14.9	0.308	0.054	21.2	0.354	0.100	39.2
UK	0.423	0.428	0.005	1.3	0.435	0.012	2.8	0.453	0.030	7.1	0.456	0.034	7.9	0.469	0.046	10.8	0.501	0.079	18.6
Europe	0.453	0.458	0.004	1.0	0.463	0.010	2.2	0.479	0.026	5.6	0.481	0.028	6.2	0.492	0.039	8.5	0.521	0.068	15.0

Note: G is the Gini index. CL is partial closure, while 1m, 2m and 3m refer to 1 month, 2 months and 3 months, respectively. $\Delta^A G$ is the absolute change in wage inequality, while $\Delta^R G$ is the relative change (%) in wage inequality.

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Table 4. Wage inequality changes in Europe (MLD).

Country	Baseline	T 1m	$\Delta^A T$	$\Delta^R T$	T 2m	$\Delta^A T$	$\Delta^R T$	T 4m	$\Delta^A T$	$\Delta^R T$	T 1m+CL	$\Delta^A T$	$\Delta^R T$	T 2m+CL	$\Delta^A T$	$\Delta^R T$	T 4m+CL	$\Delta^A T$	$\Delta^R T$
Austria	0.327	0.393	0.066	20.3	0.400	0.073	22.4	0.420	0.093	28.3	0.422	0.094	28.9	0.434	0.107	32.6	0.467	0.140	42.8
Belgium	0.185	0.300	0.115	61.9	0.306	0.121	65.1	0.325	0.140	75.4	0.326	0.141	75.8	0.339	0.153	82.7	0.373	0.188	101.5
Bulgaria	0.377	0.449	0.071	19.0	0.456	0.079	21.0	0.477	0.100	26.5	0.480	0.103	27.4	0.495	0.118	31.2	0.534	0.157	41.6
Switzerland	0.306	0.374	0.069	22.4	0.380	0.074	24.3	0.397	0.091	29.8	0.400	0.095	31.0	0.412	0.107	34.9	0.446	0.140	45.7
Cyprus	0.281	0.397	0.116	41.1	0.407	0.126	44.8	0.434	0.153	54.5	0.447	0.165	58.8	0.466	0.185	65.6	0.516	0.235	83.4
Czechia	0.160	0.302	0.141	88.2	0.310	0.149	93.3	0.333	0.173	108.0	0.329	0.168	105.0	0.343	0.183	114.0	0.383	0.223	139.1
Germany	0.329	0.396	0.066	20.1	0.401	0.072	21.9	0.417	0.088	26.7	0.423	0.094	28.5	0.434	0.105	31.7	0.463	0.133	40.5
Denmark	0.221	0.310	0.089	40.2	0.317	0.096	43.3	0.337	0.116	52.7	0.323	0.103	46.4	0.333	0.112	50.9	0.361	0.140	63.2
Estonia	0.269	0.367	0.098	36.6	0.373	0.105	39.0	0.393	0.124	46.2	0.395	0.127	47.1	0.408	0.140	52.0	0.445	0.176	65.6
Spain	0.345	0.412	0.067	19.5	0.420	0.076	21.9	0.442	0.098	28.3	0.448	0.103	29.9	0.463	0.118	34.2	0.502	0.157	45.6
Finland	0.220	0.323	0.103	46.5	0.329	0.109	49.4	0.349	0.129	58.5	0.350	0.129	58.7	0.363	0.143	64.7	0.400	0.180	81.7
France	0.285	0.368	0.084	29.4	0.373	0.089	31.2	0.390	0.105	36.9	0.389	0.105	36.8	0.401	0.116	40.8	0.433	0.149	52.3
Greece	0.288	0.372	0.084	29.2	0.379	0.090	31.3	0.397	0.109	37.8	0.409	0.121	41.8	0.424	0.136	47.0	0.465	0.177	61.4
Croatia	0.192	0.328	0.136	71.1	0.337	0.145	75.5	0.361	0.169	88.1	0.368	0.176	91.6	0.385	0.193	100.5	0.431	0.239	124.6
Hungary	0.264	0.350	0.086	32.6	0.356	0.092	34.8	0.375	0.110	41.8	0.374	0.110	41.5	0.386	0.122	46.0	0.420	0.156	59.0
Ireland	0.358	0.437	0.079	22.0	0.446	0.088	24.5	0.469	0.110	30.8	0.472	0.114	31.8	0.487	0.128	35.8	0.523	0.165	46.0
Italy	0.279	0.382	0.103	37.1	0.389	0.111	39.7	0.410	0.131	47.1	0.415	0.136	48.9	0.429	0.151	54.1	0.469	0.190	68.2
Lithuania	0.308	0.406	0.097	31.6	0.413	0.105	34.1	0.434	0.126	40.9	0.431	0.123	40.0	0.445	0.137	44.6	0.485	0.177	57.3
Luxembourg	0.292	0.398	0.106	36.2	0.407	0.115	39.2	0.429	0.137	46.8	0.427	0.134	46.0	0.440	0.148	50.7	0.474	0.182	62.3
Latvia	0.280	0.390	0.111	39.6	0.399	0.119	42.6	0.421	0.142	50.7	0.420	0.141	50.3	0.435	0.155	55.5	0.473	0.194	69.2
Netherlands	0.272	0.369	0.097	35.7	0.374	0.102	37.5	0.388	0.116	42.7	0.393	0.121	44.7	0.404	0.132	48.6	0.433	0.161	59.2
Norway	0.199	0.302	0.103	51.6	0.307	0.107	53.8	0.322	0.123	61.7	0.330	0.130	65.4	0.341	0.142	71.3	0.375	0.176	88.2
Polonia	0.217	0.338	0.121	55.7	0.345	0.128	58.8	0.365	0.148	67.9	0.371	0.154	70.9	0.385	0.168	77.2	0.423	0.205	94.5
Portugal	0.279	0.403	0.124	44.5	0.413	0.134	48.0	0.438	0.159	57.0	0.436	0.157	56.2	0.452	0.173	62.1	0.495	0.216	77.3
Romania	0.317	0.347	0.031	9.7	0.354	0.037	11.8	0.374	0.058	18.2	0.372	0.056	17.5	0.387	0.070	22.1	0.428	0.111	35.1
Sweden	0.192	0.294	0.101	52.8	0.300	0.108	56.1	0.320	0.128	66.8	0.322	0.130	67.6	0.336	0.143	74.7	0.373	0.181	94.4
Slovenia	0.215	0.335	0.119	55.4	0.343	0.128	59.4	0.366	0.151	70.2	0.363	0.148	68.7	0.378	0.163	75.6	0.418	0.203	94.1
Slovakia	0.123	0.259	0.136	110.9	0.266	0.143	116.7	0.289	0.166	135.6	0.292	0.169	138.0	0.308	0.185	151.0	0.354	0.231	188.3
UK	0.349	0.428	0.079	22.7	0.435	0.086	24.6	0.453	0.104	29.8	0.456	0.108	30.8	0.469	0.120	34.3	0.501	0.153	43.7
Europe	0.421	0.458	0.037	8.7	0.463	0.042	10.1	0.479	0.058	13.8	0.481	0.060	14.3	0.492	0.071	16.9	0.521	0.100	23.8

Note: T is the Mean Logarithmic Deviation. CL is partial closure, while 1m, 2m and 3m refer to 1 month, 2 months and 3 months, respectively. $\Delta^A T$ is the absolute change in wage inequality, while $\Delta^R T$ is the relative change (%) in wage inequality.

Our lockdown simulations show, an increase in overall inequality in workers' salary. For example, total inequality in Europe increases 4.27% (0.421 to 0.439) according to the MLD index under a lockdown of two months. For the same scenario, the changes in the between- and within-countries inequality components are 2.44% (from 0.125 to 0.128) and 5.04% (from 0.296 to 0.311), respectively. Thus, both components of overall inequality increase, although their change is not the same, the within-countries inequality component increases significantly more than the between-countries inequality component. That is, cohesion between European countries decreases with the lockdown, although the main change in wage inequality happens within European countries. With the duration of the lockdown and the partial closure of some activities, the value of the changes gets bigger and the double process of wage divergence (between and within) deepens in Europe.

Table 5. The between- and within-countries inequality components in Europe.

	Gini	T (MLD)	T^{BT}	%	T^{WT}	%
BASELINE	0.453	0.421	0.125	29.7	0.296	70.3
Lockdown 1m	0.458	0.429	0.127	29.5	0.302	70.5
Δ^A	0.004	0.008	0.001		0.006	
Δ^R	**0.97**	**1.86**	**1.17**		**2.16**	
Lockdown 2m	0.463	0.439	0.128	29.2	0.311	70.8
Δ^A	0.010	0.018	0.003		0.015	
Δ^R	**2.20**	**4.27**	**2.44**		**5.04**	
Lockdown 4m	0.479	0.469	0.132	28.2	0.337	71.8
Δ^A	0.026	0.048	0.007		0.041	
Δ^R	**5.65**	**11.32**	**5.38**		**13.83**	
Lockdown 1m + Partial Closure 6m	0.481	0.480	0.130	27.1	0.350	72.9
Δ^A	0.028	0.059	0.005		0.054	
Δ^R	**6.16**	**13.96**	**3.70**		**18.31**	
Lockdown 2m + Partial Closure 6m	0.492	0.504	0.132	26.1	0.373	73.9
Δ^A	0.039	0.083	0.007		0.077	
Δ^R	**8.51**	**19.78**	**5.24**		**25.94**	
Lockdown 4m + Partial Closure 6m	0.521	0.583	0.136	23.4	0.447	76.6
Δ^A	0.068	0.162	0.011		0.151	
Δ^R	**14.96**	**38.48**	**8.82**		**51.03**	

Note: Δ^A is the absolute change in wage inequality; Δ^R is the relative change (%) in wage inequality.

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5. Conclusions

The emergency measures adopted to contain the spread of Covid-19 all around the world are mainly based on social distancing. Unfortunately, the supply shock due to the paralysis of production imposed by the contention measures implies high economic costs to our economies in terms of GDP contraction. Moreover, given the uneven impact of social enforced distancing on different occupations and industries, these measures could have relevant distributional implications. In this paper, we have explored such effects and evaluated the potential impact of enforced social distancing on poverty and wage inequality for Europe.

Under a lockdown, only workers with essential and non-closed teleworkable occupations can work. Aiming to measure the exposure to wage loss for workers unable to work in this circumstance, we first have computed a teleworking index for all occupations. We observe that average teleworking varies significantly not only across countries (from 0.24 in Romania to 0.48 in Denmark), but also by gender, type of work, type of contract and level of education. Then, considering also the differential status of essential workers and the closure of some activities, we have derived the Lockdown Working Ability index. With this index at hand we have estimated the potential wage losses experienced by European workers under six possible lockdown scenarios corresponding to short- and medium-run.

Poverty increases for the mean loss rate of the poor and the headcount index under all simulations in all countries. And these increases are quite substantial: under a lockdown of two months, the mean loss rate for the poor would be of 10.3% of the wage and the headcount index would increase 3 percentage points on average in Europe. Nonetheless, the poverty changes vary with the European country under consideration. Likewise, wage inequality increases for both the Gini and the MLD indices under all simulations in all countries. Thus, under a lockdown of two months, the changes in the Gini coefficient and the MLD index are 2.2% and 10.1% for Europe as a whole, respectively. Again, changes are sizeable and would increase with the duration of the lockdown and when considering an additional partial closure of some activities in all countries during the de-escalation period. Considering 6 months of partial closure after a two-month lockdown, we estimate a Gini increase of 8.5% in overall Europe, a mean loss rate of 22.3% for the poor workers

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and a change of 9.8 percentage points in the poverty headcount index. For the decomposition of overall inequality in Europe, both within countries and between countries inequality increase with the duration of the lockdown and the partial closure of some activities. For example, under a lockdown of two months, within-countries inequality increases 5.0%, while between-countries inequality increases 2.4%. Therefore, in absence of any public policy across Europe, a lockdown will most probably worsen cohesion in Europe, not only between countries but especially within countries.

Our analysis of the potential effects that social distancing can have on workers all around Europe is certainly not complete and leaves out other relevant dimensions. As said in the Introduction, our analysis does not consider the demand-side changes due to individuals' response to the pandemic, nor the subsequent second-order effects in supply. These effects are clearly important but difficult to estimate at this early stage. We also ignore other welfare dimensions that could be certainly affected by the pandemic, like health. While essential workers may be more likely to keep working during the lockdown and not suffer wage losses, many of them −like health and other frontline workers− face a greater exposure to the disease (Barbieri et al., 2020). This could make this group of workers to be the most affected if health inequalities were considered.

Nonetheless, and even without accounting for second round effects that could reinforce this asymmetric impact, our limited analysis already reveals a sizable potential increase in poverty and inequality in European countries. The results of this paper are by no means a call for the early relaxation of containment measures since not properly stopping the pandemic could have devastating effects for the society as a whole. On the contrary, our paper flags up the potential distributional consequences social distancing may have if counteracting public policies are not implemented.

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Appendix A: Industries and occupations in the EU-LFS and EU-SILC databases.

Table 1. ISCO-08 and NACE digit levels by countries in EU-LFS and EU-SILC.

		EU-LFS		EU-SILC		Indexes (EU-SILC)		
	Country	ISCO	NACE	ISCO	NACE	Teleworking	Essential	Closed
AT	Austria	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
BE	Belgium	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
BG	Bulgaria*	2d	1d	1d	1d	ISCO 1d	I(1d) N(1d)	I(1d) N(1d)
CH	Switzerland	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
CY	Cyprus	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
CZ	Czech Republic	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
DE	Germany*	3d	1d	1d	1d	ISCO 2d	I(1d) N(1d)	I(1d) N(1d)
DK	Denmark*	3d	No info	2d	No info	ISCO 2d	I(2d)	I(2d)
EE	Estonia	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
ES	Spain	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
FI	Finland	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
FR	France	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
GR	Greece	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
HR	Croatia	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
HU	Hungary	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
IE	Ireland	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
IT	Italy	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
LT	Lithuania	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
LU	Luxembourg	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
LV	Latvia	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
NL	The Netherlands	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
NO	Norway	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
PL	Poland*	2d	1d	1d	1d	ISCO 1d	I(1d) N(1d)	I(1d) N(1d)
PT	Portugal	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
RO	Romania	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
SE	Sweden	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
SI	Slovenia*	2d	1d	1d	1d	ISCO 1d	I(1d) N(1d)	I(1d) N(1d)
SK	Slovak Republic	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)
UK	United Kingdom	3d	1d	2d	1d	ISCO 2d	I(2d) N(1d)	I(2d) N(1d)

Note: "d" means digit; "I" is for ISCO and "N" is for NACE in columns 8 and 9.

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Appendix B: The categorization of essential and closed occupations in Europe.

Our classification of occupations is mainly based on the Royal Decree 463/2020 (Boletin Oficial del Estado, 14th March, 2020) approved by the government of Spain on March 14th (2020). We have also considered: the Royal Decree 10/2020 (Boletin Oficial del Estado, 29th March, 2020) approved by the government of Spain on March 29th (2020); the Decree Law 23 (Gazzetta Ufficiale della Repubblica Italiana, 23rd February, 2020) and the Decree Law 25 (Gazzetta Ufficiale della Repubblica Italiana, 25th March, 2020) approved by the government of Italy on February 23rd (2020) and March 25th (2020), respectively. We explain now the main criteria followed in our categorization of occupations in Tables B3 and B4.

All occupations in industries A (Agriculture, forestry and fishing) and O (Public administration and defence; Compulsory social security), and occupations 22 (Health professionals) and 32 (Health associate professionals) −for all industries− are classified as entirely essential (1 point) under the lockdown. Most of the occupations in industry Q (Human health and social work activities) are also considered as completely essential. Meanwhile, the majority of occupations in industries B-E (Mining and quarring; Manufacturing; Electricity, gas, steam and air conditioning supply; Water supply, Sewerage, waste management and remediation activities) receive a value of essentiality equal to 0.1 because some of them (in particular electricity, gas, water supply and sewerage) are fundamental for the correct functioning of the economy during the lockdown.[14] In the same manner, most of the occupations in industry H (Transportation and storage) receive a value of essentiality equal to 0.5 since the Royal Decree 463/2020 have declared 50% of minimum services in transportation. For most occupations in industries J (Information and communication) and K (Financial and insurance activities), the given value of essentiality is 0.25 since the Spanish decree considered that a minimum service of banking and press (part of the communication industry) was deemed essential and this is approximately the percentage of activities in these industries that keep functioning under the lockdown.

With respect to the closed occupations under the lockdown, we have that all occupations −except 22 and 32− in industries G (Wholesale and retail trade; Repair of Motor Vehicles

[14] From the EU-LFS database, with greater industry disaggregation, we know that the 'water supply and electricity' share in industries B-E lies between 5% and 10% in European economies.

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and Motorcycles), I (Accommodation and food service activities) and R-T (Arts, entertainment and recreation; Other service activities; Activities of households as employers; Undifferentiated goods and services; Producing activities of households for own use) are classified as completely closed. Likewise, occupations 26 (Legal, social and cultural professionals), 34 (Legal, social, cultural and related associate professionals) and 52 (sales workers) receive a value of closure equal to 0.75 since the Royal Decree 463/2020 have declared that, among all legal activities, only the criminal legal activities should function under the lockdown, and that social and cultural activities and non-online sales are temporary forbidden to prevent people from getting together in large groups.

The values shown in Tables B3 and B4 correspond to the essential and closed occupations at the ISCO-08 2-digit level and NACE (Rev.2) 1-digit level. Based on these Tables, we calculate the values at the ISCO-08 1-digit level and NACE (Rev.2) 1-digit level (Tables B5 and B6), and the ISCO-08 2-digit level (Table B7) by averaging occupations and industries.

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Table B1. Overview of the NACE Rev.2 codes and their description.

NACE code	Description
A	Agriculture, Forestry and Fishing
B	Mining and Quarrying
C	Manufacturing
D	Electricity, Gas, Steam and Air Conditioning Supply
E	Water Supply; Sewerage, Waste Management and Remediation Activities
F	Construction
G	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles
H	Transportation and Storage
I	Accommodation and Food Service Activities
J	Information and Communication
K	Financial and Insurance Activities
L	Real Estate Activities
M	Professional, Scientific and Technical Activities
N	Administrative and Support Service Activities
O	Public Administration and Defence; Compulsory Social Security
P	Education
Q	Human Health and Social Work Activities
R	Arts, Entertainment and Recreation
S	Other Service Activities
T	Activities of Households as Employers; Undifferentiate Goods and Services Producing Activities of Households for Own Use
U	Activities of Extraterritorial Organisations and Bodies

Note: we exclude industry U in our analysis.

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Table B2. Overview of the ISCO-08 codes and their description.

ISCO code	Description
11	Chief Executives, Senior Officials and Legislators
12	Administrative and Commercial Managers
13	Production and Specialized Services Managers
14	Hospitality, Retail and Other Services Managers
21	Science and Engineering Professionals
22	Health Professionals
23	Teaching Professionals
24	Business and Administration Professionals
25	Information and Communications Technology Professionals
26	Legal, Social and Cultural Professionals
31	Science and Engineering Associate Professionals
32	Health Associate Professionals
33	Business and Administration Associate Professionals
34	Legal, Social, Cultural and Related Associate Professionals
35	Information and Communications Technicians
41	General and Keyboard Clerks
42	Customer Services Clerks
43	Numerical and Material Recording Clerks
44	Other Clerical Support Workers
51	Personal Services Workers
52	Sales Workers
53	Personal Care Workers
54	Protective Services Workers
61	Market-oriented Skilled Agricultural Workers
62	Market-oriented Skilled Forestry, Fishery and Hunting Workers
63	Subsistence Farmers, Fishers, Hunters and Gatherers
71	Building and Related Trades Workers (excluding Electricians)
72	Metal, Machinery and Related Trades Workers
73	Handicraft and Printing Workers
74	Electrical and Electronic Trades Workers
75	Food Processing, Woodworking, Garment and Other Craft and Related Trades Workers
81	Stationary Plant and Machine Operators
82	Assemblers
83	Drivers and Mobile Plant Operators
91	Cleaners and Helpers
92	Agricultural, Forestry and Fishery Labourers
93	Labourers in Mining, Construction, Manufacturing and Transport
94	Food Preparation Assistants
95	Street and Related Sales and Services Workers
96	Refuse Workers and Other Elementary Workers

Note: we exclude occupation 63 in our analysis.

Table B3. Categorization of essential occupations in Europe by Isco (2 digits) and Nace.

Isco\Nace	A	B-E	F	G	H	I	J	K	L-N	O	P	Q	R-T
11	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
12	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
13	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
14	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
21	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
22	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
24	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
25	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
26	1	0	0	0	0	0	0	0	0	1	0	0	0
31	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
32	1	1	1	1	1	1	1	1	1	1	1	1	1
33	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
34	1	0	0	0	0	0	0	0	0	1	0	1	0
35	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
41	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
42	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
43	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
44	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
51	1	0	0	0	0	0	0	0	0	1	0	0	0
52	1	0	0	0	0	0	0	0	0	1	0	0	0
53	1	0.1	0	1	0	0	0.25	0.25	0	1	0	1	0
54	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
61	1	0.1	0	0	0	0	0.25	0.25	1	1	0	0	1
62	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
71	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
72	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
73	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
74	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
75	1	0.1	0	0	0	0.25	0.25	0.25	0	1	0	0	0
81	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
82	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0	0
83	1	0.1	0	0	0.5	0.25	0.25	0.25	0	1	0	0.5	0
91	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
92	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	0	0
93	1	0.1	0	0	0.25	0	0.25	0.25	0	1	0	0	0
94	1	0.1	0	1	0.25	0.25	0.25	0.25	0	1	0	1	0
95	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
96	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0

Note: see Tables A1 and A2 for the explanation of the entries of this table. The grouping of industries follows the one adopted in EU-SILC.

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Table B4. Categorization of closed occupations in Europe by Isco (2 digits) and Nace.

Isco\ Nace	A	B-E	F	G	H	I	J	K	L-N	O	P	Q	R-T
11	0	0	0	1	0	1	0	0	0	0	0	0	1
12	0	0	0	1	0	1	0	0	0	0	0	0	1
13	0	0	0	1	0	1	0	0	0	0	0	0	1
14	0	0	0	1	0	1	0	0	0	0	0	0	1
21	0	0	0	1	0	1	0	0	0	0	0	0	1
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	1	0	1	0	0	0	0	0	0	1
24	0	0	0	1	0	1	0	0	0	0	0	0	1
25	0	0	0	1	0	1	0	0	0	0	0	0	1
26	0	0.75	0.75	0.75	0.75	1	0.75	0.75	0.75	0	0.75	0	1
31	0	0	0	1	0	1	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	1	0	1	0	0	0	0	0	0	1
34	0	0.75	0.75	0.75	0.75	1	0.75	0.75	0.75	0	0.75	0	1
35	0	0	0	1	0	1	0	0	0	0	0	0	1
41	0	0	0	1	0	1	0	0	0	0	0	0	1
42	0	0	0	1	0	1	0	0	0	0	0	0	1
43	0	0	0	1	0	1	0	0	0	0	0	0	1
44	0	0	0	1	0	1	0	0	0	0	0	0	1
51	0	1	1	1	1	1	1	1	1	0	1	0	1
52	0	0.75	0.75	0.75	0.75	0	0	0	1	0	0.75	0	1
53	0	0	0	0	0	1	0	0	0	0	0	0	1
54	0	0	0	1	0	1	0	0	0	0	0	0	1
61	0	0	0	1	0	1	0	0	0	0	0	0	0
62	0	0	0	1	0	1	0	0	0	0	0	0	1
71	0	0	0	1	0	1	0	0	0	0	0	0	1
72	0	0	0	1	0	1	0	0	0	0	0	0	1
73	0	0	0	1	0	1	0	0	0	0	0	0	1
74	0	0	0	1	0	1	0	0	0	0	0	0	1
75	0	0	0	1	0	0	0	0	0	0	1	0	1
81	0	0	0	1	0	1	0	0	0	0	0	0	1
82	0	0	0	1	0	1	0	0	0	0	0	0	1
83	0	0	0	1	0	0	0	0	0	0	0	0	1
91	0	0	0	1	0	1	0	0	0	0	1	0	1
92	0	0	0	1	0	1	0	0	0	0	0	0	1
93	0	0	0	1	0	1	0	0	0	0	0	0	1
94	0	0	0	0	0	0	0	0	0	0	0	0	1
95	0	0	0	1	0	1	0	0	0	0	0	0	1
96	0	0	0	1	0	1	0	0	0	0	0	0	1

Note: see Tables A1 and A2 for the explanation of the entries of this table. The grouping of industries follows the one adopted in EU-SILC.

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Table B5. Categorization of essential occupations in Europe by Isco (1 digit) and Nace.

Isco\Nace	A	B-E	F	G	H	I	J	K	L-N	O	P	Q	R-T
1	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
2	1	0.1	0	0	0.3	0	0.25	0.25	0	1	0	1	0
3	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	1	0
4	1	0.1	0	0	0.25	0	0.25	0.25	0	1	0	1	0
5	1	0	0	0	0	0	0.25	0.25	0	1	0	1	0
6	1	0.1	0	0	0	0	0.25	0.25	0	1	0	1	0
7	1	0.1	0	0	0	0	0.25	0.25	0	1	0	0.25	0
8	1	0.1	0	0	0.5	0	0.25	0.25	0	1	0	0	0
9	1	0.1	0	0	0.15	0	0.25	0.25	0	1	0	1	0
0	1	0.1	1	0	1	0	1	1	0	1	0	1	0

Note: see Tables A1 and A2 for the explanation of the entries of this table. The grouping of industries follows the one adopted in EU-SILC.

Table B6. Categorization of closed occupations in Europe by Isco (1 digit) and Nace.

Isco\Nace	A	B-E	F	G	H	I	J	K	L-N	O	P	Q	R-T
1	0	0	0	1	0	1	0	0	0	0	0	0	1
2	0	0	0	1	0	1	0	0	0	0	0	0	1
3	0	0	0	1	0	1	0	0	0	0	0	0	1
4	0	0	0	1	0	1	0	0	0	0	0	0	1
5	0	0.5	0.5	1	0.5	1	0	0	0	0	0.5	0	1
6	0	0	0	1	0	1	0	0	0	0	0	0	1
7	0	0	0	1	0	1	0	0	0	0	0	0	1
8	0	0	0	1	0	1	0	0	0	0	0	0	1
9	0	0	0	1	0	1	0	0	0	0	0	0	1
0	0	0	0	1	0	1	0	0	0	0	0	0	1

Note: see Tables A1 and A2 for the explanation of the entries of this table. The grouping of industries follows the one adopted in EU-SILC.

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Table B7. Categorization of essential and closed occupations in Europe by Isco (2 digits).

Isco	Essential	Closed
11	0.5	0
12	0.1	0
13	0.1	0
14	0	0.25
21	0	0
22	1	0
23	0	0
24	0.1	0
25	0.25	0
26	0	0.75
31	0	0
32	1	0
33	0	0
34	0	0.75
35	0.25	0
41	0.1	0
42	0	0
43	0.1	0
44	0.1	0
51	0	0.5
52	0	0.75
53	0.75	0
54	0.25	0
61	1	0
62	1	0
71	0	0
72	0	0
73	0	0
74	0.1	0
75	0.25	0
81	0	0
82	0	0
83	0	0
91	0.25	0
92	1	0
93	0.25	0
94	0.25	0
95	0	0.75
96	0.25	0

Note: see Table A2 for the explanation of the entries of this table.

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