Twin Peaks: Covid-19 and the Labor Market[*]

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Abstract

This paper develops a choice-theoretic equilibrium model of the labor market in the presence of a pandemic. It includes heterogeneity in productivity, age and the ability to work from home. Worker and firm behavior changes in the presence of the virus, which itself has equilibrium consequences for the infection rate. The model is calibrated to the UK and counterfactual lockdown measures are evaluated. We find a different response in both the evolution of the virus and the labor market with different lockdown policies. A laissez-faire approach results in lives lost and acts as negative shock to the economy. A lockdown policy, absent any other intervention, will reduce the lives lost but increase the economic burden. Consistent with recent evidence, we find that the economic costs from lockdown are most felt by those earning the least. Finally, we introduce a job retention scheme as implemented by the UK Government and find that it spreads the economic hardship more equitably.

Keywords: Covid-19, SIR model, search and matching, lockdown, furlough

JEL Classification: I1, I3, J1, J6

1 Introduction

The Covid-19 outbreak has posed significant global challenges to public health and the economy. Since the first cases of infection reported in China in January 2020, there have been more than 140 million cases reported worldwide and the virus has killed almost 3 million people. In the United Kingdom (UK), it has caused the death of more than 120 thousand people, with a daily peak of 1361 deaths suffered on January 19, 2021 (Figure 1). Economically, the FTSE 100 fell by 25% in the first three months of 2020, the largest quarterly fall in over three decades, and, at the time of writing, still remains below the pre-pandemic level. Workers in the economy have been particularly hard hit, with the Department of Work and Pensions processing more than ten times the typical level of benefit claims (see the second panel of Figure 1) and a 2.2 million increase in the number of benefit recipients between March and May 2020.[1] Public lockdown policies, aimed at reducing the spread of the infection and ultimately saving lives, further exacerbate the economic costs associated with the pandemic.
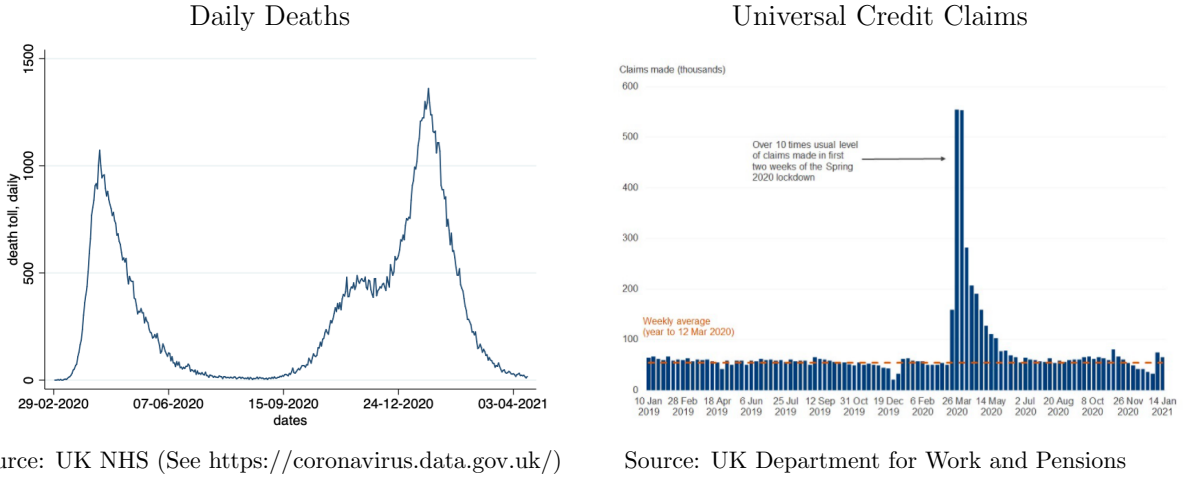
This paper merges two workhorse models from epidemiology and economics to garner a deeper understanding of the interaction between the health and economic costs associated with the pandemic. Using the UK as a case study, we examine the implications of different lockdown policies on fatalities and the economy. We find absent any intervention 1.3% of the population will pass away from the virus and the economy will shrink by 3% after one year. Health costs can be mitigated through the use of lockdown policies, at the expense of greater overall economic costs, while also disproportionately affecting low wage workers. Finally, we find the UK Government's 'Coronavirus Job Retention Scheme' helped to distribute the economic costs more uniformly and improved aggregate health outcomes.

Our paper emphasizes the important role for population and worker heterogeneity when analyzing the impact of lockdown policies. The model incorporates the SIR model of infectious diseases (Kermack and McKendrick (1927)) with the Diamond-Mortensen-Pissarides (DMP) model of the labor market (Diamond (1982), Pissarides (1985) and Mortensen and Pissarides (1994)). In order to study how the burden of economic costs and health benefits of different lockdown measures are distributed across the population, we add three sources of heterogeneity not present in the prototypical versions of either class of model.

The first form of heterogeneity we incorporate is age. Looking at any country the most striking feature regarding the composition of fatalities is age — Covid-19 is far more dangerous for the old than the young. From the epidemiology perspective that means higher mortality rates for the old. Using data on fatality rates we calibrate a mortality rate for the over 65s to be twenty times larger than for those under 65s. As a consequence, the old stand to benefit more along the health dimension from lockdown policies than the young.

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[1]See https://www.gov.uk/government/statistics/universal-credit-statistics-29-april-2013-to-14-january-2021/universal-credit-statistics-29-april-2013-to-14-january-2021

Figure 1: The UK's health and economic cost of Covid-19

Daily Deaths

Universal Credit Claims

Source: UK NHS (See https://coronavirus.data.gov.uk/)

Source: UK Department for Work and Pensions

We find that lockdown policies have a near-negligible impact on the probability of dying from Covid-19 for a young person just entering the labor force. Relative to laissez-faire, a six month lockdown reduces a 70 year old's probability of death by 11%, from 1.55% to 1.35%.

A second dimension of heterogeneity in our model is wages. Empirical studies on the Covid-19 pandemic have shown that people in low wage jobs face far greater income and employment risk than those in high wage jobs, (for the UK context see Adams-Prassl et al. (2020)). We quantify the impact of the pandemic and differing lockdown measures on the cross-section of workers by wage. Our results show that a lockdown policy reduces the risk of infection and decreases earnings across the distribution. Moreover, workers at the lower end of the wage distribution suffer a considerably larger increase in the probability of joblessness. The UK 'Coronavirus Job Retention Scheme' helped to mitigate the differential effect across the wage distribution, disproportionately protecting low wage earners from layoffs and wage cuts

Our final element of heterogeneity is in terms of the fraction of work tasks that can be completed from home in any match. We introduce a production function that depends on this fraction, in addition to the inherent productivity of a match. While spending more time working away from home can increase total production, in a pandemic it will also increase a worker's exposure to the virus. Susceptible workers who are very productive from home, thereby foregoing little production and little of their wage, will choose to do so when the infection rate is high, slowing the spread of the pandemic. However, not all workers are afforded this luxury and as will be shown these less *lucky* workers tend to be in low paid work. Even in the absence of lockdown policy, workers will work more from home and they will do so out of self-interest. When making this decision however, they do not internalize

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the negative externality of becoming infected on increasing the infection rate for society as a whole. This market failure additionally motivates the need for government intervention in locking down a section of the economy.

Related literature. Before the Covid-19 pandemic there existed a small theoretical literature which merged economic behavior to epidemiology models. In a standard model of disease transmission the '*basic reproduction rate*' is a constant — that is the average number of people one will infect given that the rest of the population is susceptible. In some sense the theoretical economic literature attempts to endogenize this rate. For a variety of mechanisms and diseases see, Kremer (1996), Quercioli and Smith (2006), Toxvaerd (2019, 2020) and Galeotti and Rogers (2013). In the context of our model the reproduction number depends on the decision of how much to work away from home made by the susceptible employed. This paper is quantitative in nature and incorporates heterogeneity in many dimensions. Again, there is a small literature before this pandemic on calibrating and simulating a quantitative model of economic agents in an epidemiological framework. For the HIV virus see Greenwood et al. (2017, 2019) and Chan et al. (2016) and for Bird-flu (and now Covid-19) Keppo et al. (2020).

Since the outbreak of the Covid-19 pandemic there is a large and expanding number of papers building on the work of the aforementioned authors. That said, to our knowledge there is only Kapička and Rupert (2020) that also explore how a frictional labor market interacts with a pandemic. However, the focus and exposition of their paper is quite different. A worker's health status segments the labor market and is the only source of heterogeneity. Interestingly there are papers that have leaned on the two building blocks of our model to understand disease spread, see Farboodi et al. (2020) and Garibaldi et al. (2020). But neither paper explicitly models the labor market. More broadly, there are a number of quantitative models that evaluate the economic and health trade-offs of the pandemic and policies. Eichenbaum et al. (2020) merge the SIR model with a neo-classical representative agent model. We argue that heterogeneity is an important factor in the pandemic and our model allows for health and economic costs to vary by age, wage and occupation. Kaplan et al. (2020) account for dispersion in occupation and assets and Brotherhood et al. (2020), Favero et al. (2020) and Glover et al. (2020) use a multi-risk SIR model to account for differential mortality by age.

Outline. The rest of the paper proceeds as follows. In section 2 we setup our baseline model of the labor market and the pandemic and we explain the role of lockdown policy. The model is calibrated to data and policy simulations are run in section 3. In section 4 we discuss the Job Retention scheme and compare the changes in welfare of the different policy regimes. Section 5 concludes.

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2 The baseline model

The environment

Time is continuous and initially the economy is populated by a unit mass of individuals who are risk neutral, either young or old and discount the future at a constant rate r. We denote age as a; for old $a = o$ and young $a = y$. Young individuals are part of the labor force and age stochastically at a Poisson rate η. A constant exogenous flow ψ of young individuals are born into unemployment. Given their age and health status workers are ex ante homogeneous and if young are ex post heterogeneous in their employment status. They can be either employed and vary in their wage w or unemployed, sustaining themselves with an exogenous flow b_u. We do not distinguish between the unemployed and the inactive and will therefore use the terms *not employed* and *unemployed* interchangeably. Old individuals are retired, they sustain themselves with exogenous flow b_o and die stochastically of natural causes at Poisson rate χ.[2] In addition to age and labor force status individuals are characterized by a health state, h, which can be either susceptible $h = s$, infected $h = i$, or recovered $h = r$.

Production

A match between a worker and a firm is characterized by two indices. A productivity index x and a technology index α, where $x, \alpha \in [0,1]$. The variable α describes the efficiency of home working relative to working away from home. The function $\tilde{h}(\alpha)$ describes the measure of tasks associated with a job that can be performed at home, where $\tilde{h} : [0,1] \to [0,1]$ and $\tilde{h}'(\alpha) > 0$. The function $g(x)$ describes the total potential output of the worker-firm pair, where $g'(x) > 0$ and $g : [0,1] \to \mathbb{R}^+$. Total output of a match is given by $p(\alpha, x, m)$ where $m \in \{0,1\}$, taking the value 0 if a worker exclusively works from home and one if they ever work away from home.

$$p(\alpha, x, 0) = g(x)\tilde{h}(\alpha) \quad \text{and} \quad p(\alpha, x, 1) = g(x) \tag{1}$$

The functions $g(\cdot)$ and $\tilde{h}(\cdot)$ will be parameterized later but notice that a worker leaving their house for work will produce an amount entirely dependent on x and output is always at least as high by working outside of the household, $p(\alpha, x, 1) \geq p(\alpha, x, 0)$. The indices α and x are drawn from a joint distribution $f(\alpha, x)$ at the time of worker-firm meeting and are fixed for the duration of the match. We allow for dependence between α and x in the distribution f and without loss of generality we assume that both have have uniform marginal distributions on $[0,1]$.

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[2]To fix the initial population to one, the parameter ψ is set accordingly as $\psi := \frac{\eta\chi}{\eta+\chi}$.

Health status

Individuals transit between three health states h: susceptible (s), infected (i) and recovered (r) according to a standard SIR epidemiology model. Our approach departs from the standard model by assuming the infection probability depends on whether employed workers work at home remotely or commute to their place of work. Susceptible agents who work from home contract the disease with a Poisson rate $\lambda_0 \ell_{it}$ where $\lambda_0 > 0$ is an exogenous fixed parameter and ℓ_{it} is the share of the population who are infected at time t. Susceptible individuals leaving the home for work face a higher rate of infection and become infected at an increased Poisson intensity $(\lambda_0 + \lambda_1)\ell_{it}$, where $\lambda_1 > 0$.[3] This introduces a clear trade-off for the worker: by working away from home their production will increase, and in turn so will their wage. However, they do so by increasing the likelihood of contracting the disease. Further, while a worker's decision will internalize the individual cost of working away from home it does not internalize the cost to society. By becoming infected, the share of the infected population ℓ_{it} will increase and so will the rate of infection at which susceptible workers of any age and employment status catch the disease.

Once infected, individuals will either recover from the disease and transition to the recovered state at Poisson rate ρ_a, or they pass away from the disease at rate γ_a. We allow the mortality of the disease to vary with with individual's age as data on recorded mortality rates differ starkly across age groups. Further, in our model being infected means a worker is not able to either look for employment if out of work or produce output if in work. Finally, being recovered is an absorbing health status.[4]

The full dynamic system will depend on the evolution of the labor market as well as the health outcomes. This system will be spelled out in detail later and can be found in full in Appendix A.2. We spell out the dynamics of the epidemiological block below. Let n_{ht}^a define the mass of individuals of health status $h \in \{s, i, r\}$ and age $a \in \{y, o\}$ at time t. Then, for the young and hence active in the labor market, the dynamics of the system can be written as below.

$$\dot{n}_{st}^y = \psi - \tilde{\lambda}_t \ell_{it} n_{st}^y - \eta n_{st}^y$$
$$\dot{n}_{it}^y = \tilde{\lambda}_t \ell_{it} n_{st}^y - (\rho_y + \gamma_y) n_{it}^y - \eta n_{it}^y$$
$$\dot{n}_{rt}^y = \rho_y n_{it}^y - \eta n_{rt}^y$$

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[3]In the model workers will not run into infected colleagues at their place of work. We think of this increased risk through traveling to work and increased exposure to other members of society while at their place of work.

[4]There is some support that, as with other coronaviruses, immunity may wane at around one year (Phillips, 2021). Giannitsarou et al. (2020) develop a behavioral SEIRS model in which the virus re-emerges in dampened cycles. We instead follow the bulk of the recent integrated epi-econ literature and we assume that those who have recovered from the virus can not contract it again. A robustness to this assumption has been explored and is available in the online appendix.

$\tilde{\lambda}_t$ is a composite infection rate, which time-varies due to the changing aggregate state of the economy and because of individual choices made by susceptible employed workers as to whether or not to work remotely. The labor market block in essence endogenizes this basic reproduction parameter. Older workers are assumed inactive in the labor market and therefore face infection risk only through the evolution of the proportion of infected in the economy at large.

$$\dot{n}_{st}^o = \eta n_{st}^y - (\lambda_0 \ell_{it} + \chi) n_{st}^o$$
$$\dot{n}_{it}^o = \eta n_{it}^y + \lambda_0 \ell_{it} n_{st}^o - (\rho_o + \gamma_o + \chi) n_{it}^o$$
$$\dot{n}_{rt}^o = \eta n_{rt}^y + \rho_o n_{it}^o - \chi n_{rt}^o$$

The labor market

The labor market is subject to search frictions. Unemployed and healthy workers can costlessly search for a job. Firms post vacancies at flow cost κ to attract potential applicants. The total measure of vacancies posted is determined by a free entry condition. On the worker's side, only the young, non-employed and non-infected can search for work. (Active) searching workers, $a_t := u_{st} + u_{rt}$, where u_{st} (u_{rt}) is the measure of susceptible (recovered) unemployed workers at time t, and unfilled vacancy, v_t, meet at a rate determined by a constant returns to scale meeting function $m(a_t, v_t)$. This implies a job finding rate for workers of ϕ_t and a worker finding rate of ϕ_t^f for firms,

$$\phi_t = \frac{m(a_t, v_t)}{a_t} \quad \text{and} \quad \phi_t^f = \frac{m(a_t, v_t)}{v_t} = \phi \frac{a_t}{v_t} \tag{2}$$

After meeting, the worker and firm draw α and x from the joint distribution f. There is no private information and the values of α, x and the health status of the worker will determine whether the meeting results in a match. Matches separate at a constant exogenous Poisson rate δ.

Contracting space

The joint surplus generated from a match is shared between worker and firm according to a Nash bargaining protocol. In a first step a contract is written to account for time devoted to working from home by maximizing joint surplus. Let $m \in \{0, 1\}$ be an indicator to denote if work is only performed at home, $m = 0$, or away from home, $m = 1$, respectively. Wage is determined to split the surplus according to the standard Nash sharing rule, where worker receives a share $\beta \in (0, 1)$ of the total surplus and the firm $(1 - \beta)$.

We denote the value functions of matched workers and firms as $W_{ht}(w, \alpha, x, m)$ and $J_{ht}(w, \alpha, x, m)$, where W is the value of being employed and J the value of a filled vacancy for the firm in a match with a worker of health status $h \in \{s, i, r\}$, with job characteristics

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(α, x) under a contract (w, m) at time t. Let U_{ht} be the value of being unemployed for a worker with health status $h \in \{s, i, r\}$ and V_t be the value of an open vacancy. We assume that the joint surplus of a match can be written independent of the wage and is given by equation (3), (which is verified ex-post)

$$S_{ht}(\alpha, x, m) = W_{ht}(w, \alpha, x, m) - U_{ht} + J_{ht}(w, \alpha, x, m) - V_t \tag{3}$$

Thus when a worker and firm meet they decide jointly on the working arrangements and choose m according to

$$\arg \max_{m \in \{0,1\}} \{S_{ht}(\alpha, x, m)\} := S_{ht}(\alpha, x).$$

The relative value of $S_{ht}(\alpha, x, 0)$ and $S_{ht}(\alpha, x, 1)$ define the work environment agreed upon at negotiation. The value of the maximum of these objects, $S_{ht}(\alpha, x)$, defines the set of feasible matches in the economy $\mathcal{M}(h, \alpha, x) = \{h, \alpha, x : S_{ht}(\alpha, x) \geq 0\}$.

Finally, after negotiating a wage and work environment both parties must comply to their contractual agreement for a stochastic length of time. We assume that if there is a change in the health status of the worker the pair can costlessly change the agreement of working at or away from home, but not their wage agreement. Otherwise they can only adjust the hours of work or wages when they re-negotiate, which happens at an exogenous Poisson rate ν. After the re-negotiation shock they may also decide to separate if the joint surplus is negative. This rigidity models in a reduced form way the inability of UK firms to layoff workers immediately after changes in policy or worker's changing health status.

Vacancy creation

Vacant jobs make contact with unemployed workers at a rate ϕ_t^f. We assume free entry such that potential firms continue to post vacancies until the presented discounted expected value of doing so is zero. The value of posting a vacancy is given by

$$rV_t = -\kappa + \phi_t^f (1 - \beta) \left(\frac{u_{st}}{u_{st} + u_{rt}} \int \int \max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\} f(\alpha, x) d\alpha dx \right.$$

$$\left. + \frac{u_{rt}}{u_{st} + u_{rt}} \int \int \max\{S_{rt}(\alpha, x), 0\} f(\alpha, x) d\alpha dx \right) \tag{4}$$

where κ is the flow cost incurred when posting a vacancy. Thus the equilibrium aggregate number of vacancies are determined by setting the left hand side of equation (4) to zero.

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Equilibrium and solving the model

The model structure allows all decisions, whether a worker-firm match is feasible and if so whether the worker should work in or away from the household, to be a function of the joint surplus of a match. This property is shown by specifying and solving the value functions in Appendix A.1. In addition one must compute the allocation of workers across demographic, health and economic status. These follow the dynamics in Appendix A.2. We assume the economy starts from a unique steady-state in which the whole population is susceptible and deviate with a *small* initial seed mass in which the probability of infection is constant across employment state. The final equilibrium object to pin down is the number of vacancies posted by firms, which given worker allocations and surpluses uniquely solves equation (4). Details of how these objects are computationally solved are provided in Appendix A.3.

Economy under lockdown

Lockdown is modeled as an exogenous and random share $\pi \in [0, 1]$ of the economy prevented from operating away from home (e.g. an office). Workers in these locked jobs are mandated to only work at home. Thus if the policy binds, a match of production index α will see their production fall by a share $(1 - \tilde{h}(\alpha))$. New jobs can either be in the '*locked*', (with probability π), or '*unlocked*' sector, (with probability $(1 - \pi)$). This draw is made at the time of worker-firm meeting and is assumed orthogonal to α and x.[5]

We model lockdown as slowing the rate of transmission through two mechanisms. Firstly, fewer people work away from their home. This reduces the number of people who contract the disease at their place of work. Those working at home have a Poisson rate of becoming infected which is $\lambda_1 \ell_{it}$ less than those working away from home. The second mechanism is through social distancing. While not explicitly modeled, a lockdown on bars and restaurants for example will reduce the number of social interactions in the economy. The parameter λ_0 governs the latent transmission rate irrespective of working decisions. Since lockdown will also affect contagion outside of the workplace, we introduce a reduced basic reproduction rate under lockdown, defined as

$$\lambda_0^L := (1 - \pi)\lambda_0.$$

The final amendment to the model is that lockdown is not permanent. While lockdown arrives as an unanticipated shock, agents assume it ends at an exogenous Poisson rate Λ after which the economy returns to the status quo. Modeling lockdown policy introduces an additional state variable for a worker-firm pair. That is, whether or not the job is '*locked*'

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[5]In future work, when survey data can be easily analyzed it would be interesting to assume two conditional distributions for $f(\cdot)$. This would allow one to evaluate the economic costs from a targeted lockdown.

or *unlocked'*, otherwise the model retains the same structure. In order to avoid repetition, we relegate the exposition and solution of the model to a complementary online appendix.

3   Quantitative results

The goal of this section is to examine the likely effects of lockdown policy on the safety of workers and the performance of the economy as a whole. Rather than being explicit about a social welfare function we simply demonstrate the trade-off between the likely number of fatalities from the pandemic and the stress to the economy caused by lockdown policy. It is necessary to begin with two home truths. Firstly, a laissez-faire approach, in the presence of the pandemic, will cause an economic downturn. That is to say, because of endogenous responses in the model, even in the absence of economic policy there will be economic losses and they are likely to be large. In particular, we find cumulative output losses to be around 2.4% of the pre-pandemic level under the laissez-faire approach over 5-year horizon. Secondly, in the absence of a vaccine, the infection exists indefinitely, irrespective of how draconian a lockdown policy may be. In fact because we model new entrants into the labor market as susceptible, in the long run the pandemic will repeat itself in dampening cycles in perpetuity. Since these cycles materialize at approximately a twenty year frequency, we abstract from these in our discussion of policy and assume by the time of the next cycle a vaccine has been developed. Consequently, all discussion will relate to the ongoing wave of the pandemic. As a preview of our results we summarize these points and other findings in the list below.

1. Lockdown will not rid us of the virus. For that a vaccine needs to be found.

2. Lockdown is not the only source of economic stress. The economy will suffer from a laissez-faire approach.

3. Absent lockdown, agents' behavior changes insufficiently to reduce lives lost significantly and a government intervention is required to mitigate the loss of life.

4. The economic costs of lockdown are not borne uniformly across the cross-section of workers: those at the lower-end of the wage distribution are affected disproportionately more.

5. The 'Coronavirus Job Retention Scheme' used by the UK government, in conjunction with lockdown, helped mitigate the loss in life further and shared the economic costs more uniformly.

Parameterization

To proceed, we begin by specifying functional forms for the matching function $m(a_t, v_t)$, the functions entering production, $g(x)$ and $\tilde{h}(\alpha)$ and the distribution of job's characteristics,

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$f(x, \alpha)$. We use a standard Cobb-Douglas function to model contacts between vacancies v and the non-employed actively searching a

$$m(a_t, v_t) = a_t^{1-\xi} v_t^{\xi},$$

where $\xi \in (0, 1)$ denotes the elasticity of contact with respect to the stock of open vacancies.[6] This matching function implies a contact rate for a vacancy of ϕ_t^f and a contact rate for workers equal to ϕ_t, where

$$\phi_t^f = \frac{m(a_t, v_t)}{v_t} = \theta_t^{\xi-1} \quad \text{and} \quad \phi_t = \frac{m(a_t, v_t)}{a_t} = \theta_t \phi_t^f.$$

The variable θ_t denotes the labor market tightness, defined as $\theta_t := v_t/a_t$. We specify the total potential output of a worker-firm pair of index x as the inverse of a log-normal distribution with underlying mean μ_x and variance σ_x^2,

$$g(x) = \exp\left(\mu_x + \sigma_x \Phi^{-1}(x)\right)$$

where $\Phi^{-1}(\cdot)$ denotes the inverse cumulative distribution function of a standard normal distribution. To describe the proportion of job tasks that can be performed at home, we assume $\tilde{h}(\alpha)$ to be an inverted Beta distribution,

$$\tilde{h}(\alpha) = \frac{\alpha^{\beta_1-1}(\alpha+1)^{-\beta_1-\beta_2}}{\mathcal{B}(\beta_1, \beta_2)}$$

where $\beta_1, \beta_2 \geq 1$ are the parameters of the beta distribution and $\mathcal{B}$ denotes the Beta function. To model correlation between job productivity x and home efficiency α, we choose the function $f(\alpha, x)$ to be a Gaussian copula with correlation parameter $\rho_{\alpha,x}$.

Calibration

The model is calibrated at a weekly frequency for the pre-pandemic period and simulations are run at a daily frequency. Table 1 reports parameters values for demographic, labor market and technology and the moments used to calibrate them. The interest rate r is set to have an annual return of 1%. Workers spend on average 40 years in the labor market, and 15 years in retirement. These values pin down aging rate η and death rate χ.

We set the re-negotiation rate to match two weeks of advance notice and fix $\nu = 0.5$.[7] We set the income flow for unemployed workers to 65% of the average wage as reported for

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[6]In this environment, the scaling parameter in the matching function is isomorphic to the cost of posting a vacancy. Therefore, without loss of generality, we normalize the former to one.

[7]The statutory redundancy notice period in the UK is in practice a function of the length of time one has been in their job. Those employed for under a month can be laid off without notice. For those employed between one month and two years, one week notice is required. Then for each additional year a further weeks notice is required, capped at twelve weeks.

Table 1: Calibrated parameters

Parameters	Description	Value	Source/Target
		Demographics	
r	Discount rate	0.00098641	Annual return: 1% annual
η	Ageing rate	0.00048077	40 years in the labor market: 25-65 y.o.
χ	Death rate	0.00128210	15 years of retirement: 65-80 y.o.
ψ	Birth rate	0.00034965	Pre-pandemic population=1
		Labor market	
ν	Re-negotiation rate	0.5	Two weeks advance notice
b_r	Retirement income flow	406.02	Equivalized disposable income retired/non-retired HH=75% (ONS)
b_u	Unemployment income flow	354.25	Average replacement rate=65% (OECD)
ξ	Matching elasticity	0.35	Turrell et al. (2018)
β	Bargaining power	0.0982	Labor share=54.63% (ONS)
δ	Job destruction rate	0.0102	Monthly job separation=4%, Postel-Vinay and Sepahsalari (2019)
κ	Vacancy cost	109189	Employment rate=76% (ONS)
		Technology	
μ_x	Output technology	4.9263	Average weekly earnings: E[w]= 545 (ONS)
σ_x	Output technology	1.2856	Vacancy per population= 1.19% (ONS)
β_1	Home-working efficiency	0.0351	Average home-working hours: E[h]= 38% Dingel and Neiman (2020)
β_2	Home-working efficiency	0.4689	90-10 ratio home-working hours: p90[h]/p10[h]= 0.88, Dingel and Neiman (2020)
$\rho_{\alpha,x}$	Copula parameter	0.9470	Corr. log weekly earnings and home-working hours: corr[logw, h]= 0.706, Dingel and Neiman (2020)
		Epidemic dynamics	
λ_0	Infection rate, basic	1.2636	Basic reproduction rate: R_0 = 2.4, Ferguson et al. (2020)
λ_1	Infection rate, at work	0.8070	Infection at work: 0.353, Houštecká et al. (2020)
γ_y	Death rate, young	0.0016	Infected fatality ratio: 0.212%, CDC (2021)
γ_o	Death rate, old	0.0343	Infected fatality ratio: 5.4%, CDC (2021)
ρ_y	Recovery rate, young	0.7	Average recovery period: ten days, Ferguson et al. (2020)
ρ_o	Recovery rate, old	0.7	Average recovery period: ten days, Ferguson et al. (2020)

the UK in 2019 by the OECD. The income flow for retired workers to 75% of the average wage, to match the ratio between equivalized disposable income of retired and non-retired HH (ONS). The bargaining power, β, is calibrated to match a value for labor share equal to 54.63% (UK national accounts 2016Q3). The matching elasticity, ξ is calibrated to match the estimated value of 0.35 in Turrell et al. (2018). The exogenous job destruction rate, δ, is calibrated to match a monthly separation rate of 4% reported in Postel-Vinay and Sepahsalari (2019).[8] Finally, we calibrate the cost of posting of vacancy, κ, to match the employment rate in the last quarter of 2019 (ONS).

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[8]Recall, we do not distinguish between the young and inactive and unemployed so take the sum of the separation rates to unemployment and inactivity at the end of their sample.

We are left with five parameters, governing productivity and home-working efficiency. We calibrate the parameters of the production technology μ_x and σ_x to match an average weekly earnings of 545 GBP (ONS Weekly Earnings Survey, February 2020) and an average stock of vacancy per population in the last quarter of 2019 of 1.19% (ONS - Vacancy Survey). Given the stock of vacancies the proportion of meetings that result in matches is driven by the degree of dispersion in the job sampling distribution.[9] Finally we choose the parameters in the inverted beta distribution, β_1 and β_2 to match average and dispersion (90-10 ratio) of home-working hours across 2-digit occupations reported in Dingel and Neiman (2020). We calibrate the copula parameter, $\rho_{\alpha,x}$, to match the correlation between number of home-working hours and average hourly wage (see Figure 1 in Dingel and Neiman (2020))

Turning to the parameters of the SIR model, we follow Ferguson et al. (2020) and calibrate λ_0 and λ_1 to match an average basic reproduction rate of 2.4 at the eve of the pandemic. From the context of the model this is the reproduction rate when the entire population is susceptible without any endogenous changes to the working environment. From the perspective of the data, this comes from the early estimates in Wuhan, again when the population was close to fully susceptible.[10] To disentangle the value of λ_0 from λ_1 we calibrate λ_1 to match how much more likely employed individuals are to be infected with the virus. Using the Medical Expenditure Panel Survey in the US, Houštecká et al. (2020) estimate this value to be 35.3%. We calibrate death rates of young and old, γ_y and γ_o, to match the infection fatality ratios in their age categories reported by the CDC's (2021) best estimate scenario.[11] Finally, we fix the average recovery period to 10 days following Ferguson et al. (2020).

Counterfactual experiments

We keep the severity of a lockdown (π) fixed and vary the duration ($1/\Lambda$). The specifics of the policy simulation are represented in Table 2. We begin with very few infected people and assume all employment states are equally likely to be infected at time zero. The economy is simulated and we assume lockdown arrives as an unanticipated shock 24 days after the first registered death, to mirror the experience of the UK. Since there is a continuum of workers in the model we interpret the first death as the number of deaths exceeding one divided by the UK's population. The proportion of the economy locked down π is calibrated to match the share of workers employed in sectors that have been shutdown during the first UK lockdown. Joyce and Xu (2020) estimate this value to be 15%. This estimate includes workers employed in non-food retail, restaurants and hotels, passenger transport, personal

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[9]To see this, imagine there were no dispersion in productivity. All worker-firm meetings will result in matches as the worker or firm have no incentive to wait and find a better match.

[10]Estimates from Riou and Althaus (2020) and Li et al. (2020) put the number somewhere between 2.0 and 2.6

[11]These estimates are based on age-weighted estimates of infection fatality ratios from Hauser et al. (2020)

Table 2: Calibration of policy parameters

Parameters	Description	Value	Source/Target/Explanation
			Practicalities
	Initial seed mass	10^{-9}	
	First death	$1/66/10^6$	
	Burnin period	24 days	Time between first death and lockdown in the UK.
			Lockdown
π	Share of economy on lockdown	0.15	Joyce and Xu (2020)

services and arts and leisure services.

Health costs. We begin by looking at the health costs of the pandemic associated with a three and six month lockdown period. The lockdown policy is shown in the first panel of Figure 2 and the associated health outcomes in the second row. Both lockdown policies are able to suppress the pandemic to some extent and will result in fewer total deaths than the laissez-faire approach — depicted in black. The three month lockdown suppresses the virus during the lockdown period, but it is lifted before the peak of infection and results in many more lives lost following the lifting of restrictions. By contrast the six month lockdown appears to break the back of the pandemic — the stock of infected being at approximately zero when lockdown is lifted. Consequently, the longer lockdown results in more lives saved and fewer people having contracted the virus at all, seen by the larger levels of susceptible individuals a year later.

Economic cost. As well as variation in the health costs associated with different lockdown policies there are also large variations in the economic consequences. As has been discussed no policy intervention is not costless from an economic point of view. Work days are lost because of illness and the increased exposure to health risks reduce the value of jobs and thus the level of vacancy posting falls. Lockdown policy will inevitably confound these losses. Primarily because it directly reduces potential output, forcing a share of jobs in the economy to limit production to inside the worker's home. Clearly, the longer the economy is restricted, the larger these losses are going to be. However the losses are also intrinsically linked to the workings of the labor market. This can be seen in the first row of Figure 2. The shorter lockdown has a much smaller initial fall in employment. Since firms know the lockdown is relatively short, firms opt to hoard their workforce. Even in the face of a considerable drop in production, firms prefer this choice over incurring hiring costs in the future; they keep their workers on the payroll and take the short term losses. Hence, a longer lockdown not only results in more persistent falls in output and employment, but the shock itself is of a larger magnitude as well.

Figure 2: Dynamics of the pandemic and economy
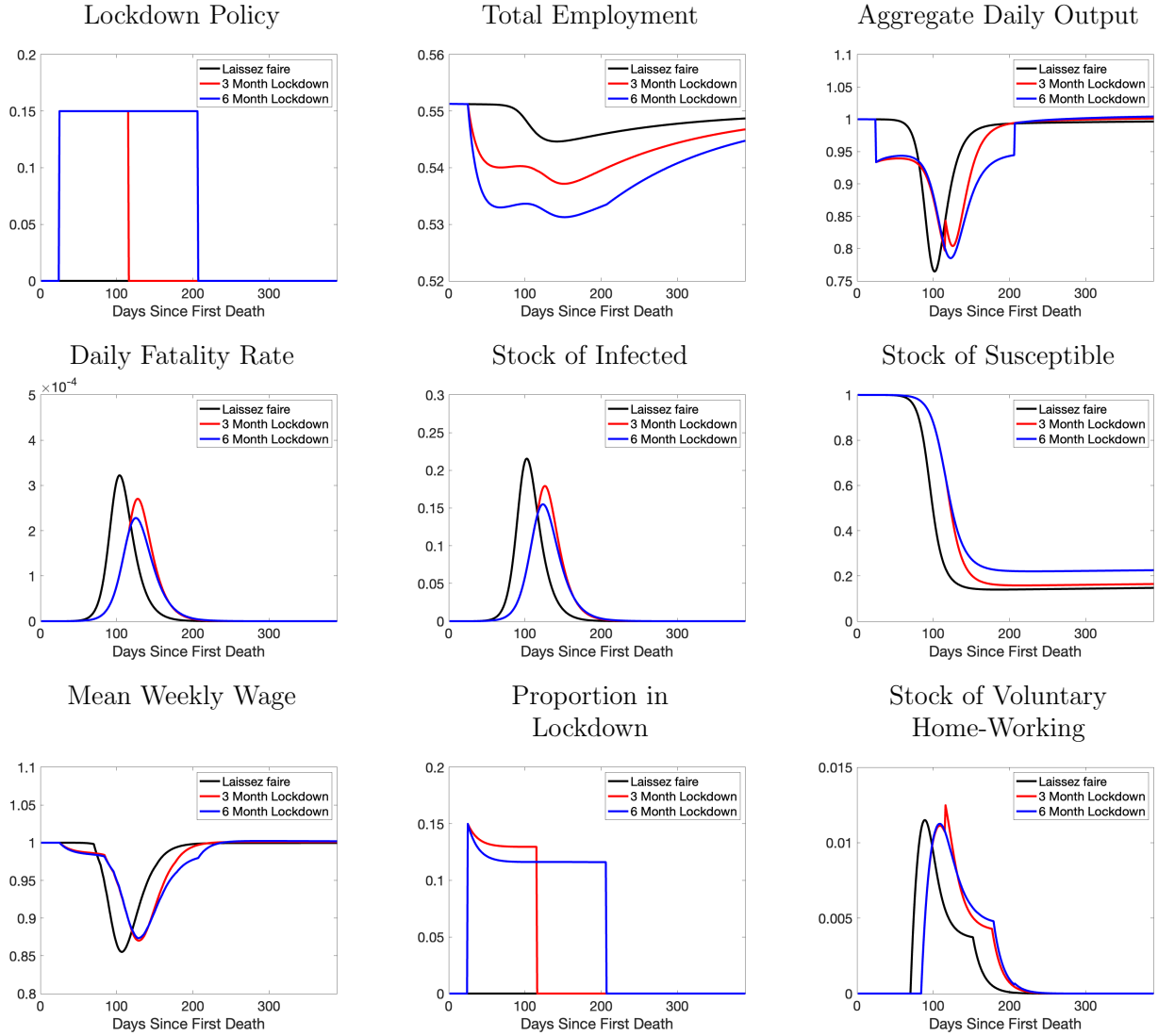
Labor adjustment. To better understand the different labor market responses to the different duration of lockdown, Figure 3 plots the response in gross hiring and firing following implementation. As discussed, the more severe lockdown results in many more layoffs, as hoarding labor for prosperous times to come becomes far more expensive. At the same time, there is also a large initial fall in hiring as many matches are locked and will not hire unless they are extremely productive or efficient in working from home. After an initial fall, the level of hiring rises steadily under both regimes. This is in part due to a larger pool of unemployed following the large rise in layoffs and in part because of workers' falling outside

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Figure 3: Labor adjustment
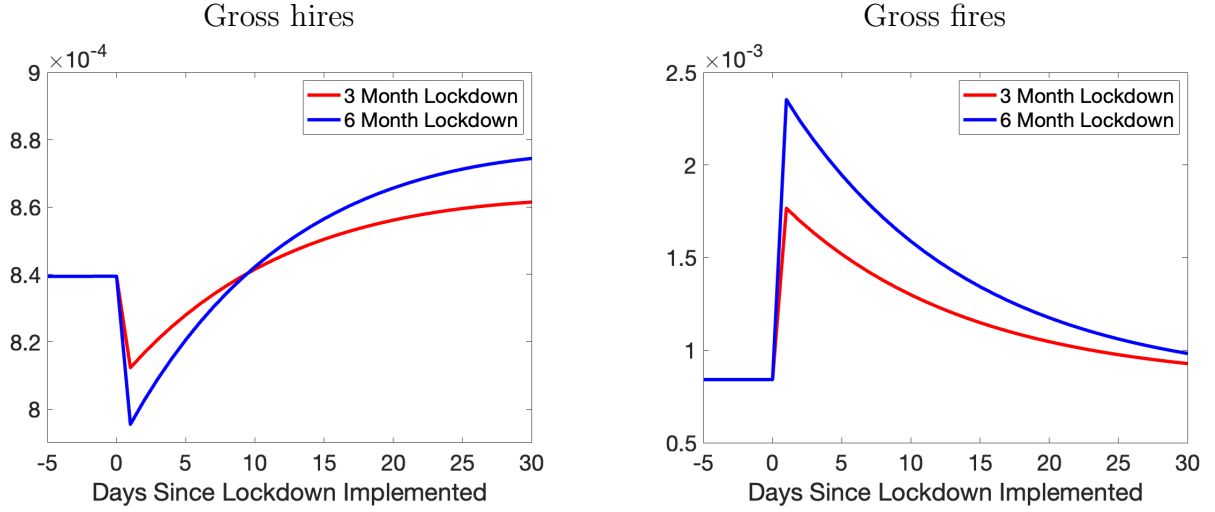
option — the deteriorating state of the economy makes them less discerning in which matches to accept. In fact, because of the enormous misallocation shock to the economy, hiring levels under both policy options eventually exceed the level of hiring pre-lockdown.

Returning to the final row of Figure 2 shows the direction that reallocation takes. Initially the share of workers subject to lockdown is the same as the proportion of the economy under lockdown. However, following layoffs based predominantly in locked sectors, and new hires being made predominantly in unlocked ones, there is a gradual decline in the fraction of the economy locked down. One can see that under all regimes wages paid to workers fall; this is driven by several factors. They are: falling outside options because of the existence of the pandemic; lost days of work when workers fall ill; and in the case of lockdown, lower productive capabilities for a share of the workforce. In fact, the average wage falls more under laissez-faire than when implementing a lockdown. Since the ability to work from home and a match's productive potential exhibit strong positive correlation it is primarily the low output and low wage jobs that are laid off in the aftermath of implementing lockdown. Thus through selection, wage losses in the aggregate under lockdown appear less severe than under a laissez-faire approach.

The final channel of labor adjustment that is apparent in the model is at the intensive margin. Rather than changing jobs some worker-firm pairs opt to change the underlying work environment associated with the match. For a susceptible worker, as discussed, working away from home increases the probability of becoming infected. If output losses are sufficiently small due to remote working, in the case that α is large, surplus is maximized when a worker works from home, $m = 0$. This margin is shown in the final panel of Figure 2. Irrespective of government intervention, workers will voluntarily work from home, reducing

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the infection rate. However, our simulations show these equilibrium effects are small. At the peak of the infection around 1% of workers switch to home working and thus endogenously reduce the viral reproduction rate at large.

Distributional effects. Figure 4 depicts the effect of the three and six month lockdown policies, in addition to a laissez-faire approach, on measures of employment, infection and wage risk. The first panel of Figure 4 shows the probability a worker ever becomes infected from one month prior to lockdown to three months post. These probabilities are plotted against their wage decile one month prior. The first thing to notice is that absent intervention a worker is far more likely to contract the virus over this period, plotted on the left hand axis. This is primarily because absent policy the virus spreads through the population much more quickly than when the virus is suppressed under lockdown policy. Interestingly, across all policies, high wage workers are slightly less likely to contract the virus. Due to the positive correlation between the proportion of tasks that can be done at home and productivity, those in high wage jobs are more able to switch to remote work and reduce the probability they contract the virus.

While the differential health costs incurred across the income distribution are relatively small, the economic costs are indeed quite large when lockdown is implemented. Absent any policy, a worker employed one month prior to when lockdown would have been introduced can expect to be unemployed three months later with approximately 14% chance. This probability is independent of their position in the income distribution. However, under lockdown this employment risk increases considerably and the increase is borne entirely by low wage workers. Under a six month lockdown a worker in the first decile of the wage distribution is eight percentage points more likely to be unemployed. The longer the duration of the lockdown the larger the magnitude of the risk and the more workers it will effect. This increase in job loss probability is consistent with the data work of Adams-Prassl et al. (2020). They find that low wage workers across a set of industrialized countries, (including the UK), faced disproportionately large employment risk during the pandemic. The final panel, shows the mean wage of a job at the peak of the infection relative to the wage that would have been paid absent a pandemic. Wages fall in the order of ten percent, in a way that is relatively uniform across the distribution. From this we infer that economic costs to all agents are large. However it is the low wage workers who really suffer — they frequently pay, arguably the largest economic cost of all, job loss.

Heterogeneous effects by age. The model and its calibration has a clear implication of the demographic winners and losers of lockdown policy. The old gain substantially more from a severe policy intervention since they are, conditional on becoming infected, far more likely to die from the virus, as $\gamma_o >> \gamma_y$. The costs of the policy come through declining labor income and employment. Since only the young participate in the labor market they not only receive less of the gains from lockdown but also bare all of the costs. Clearly there

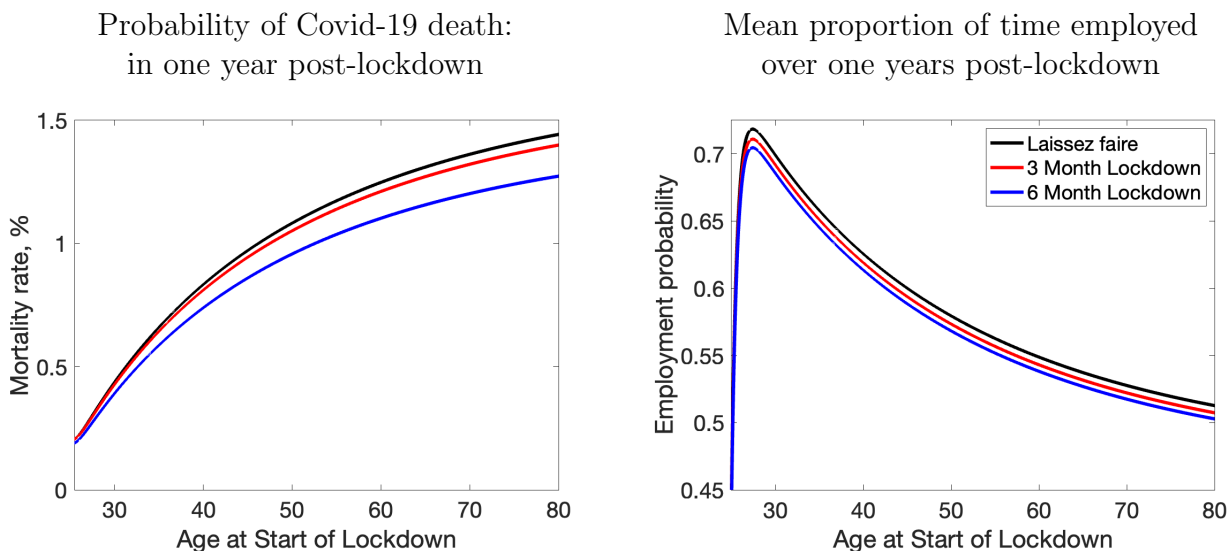Figure 4: Heterogeneous effects of policies on the worker cross-section
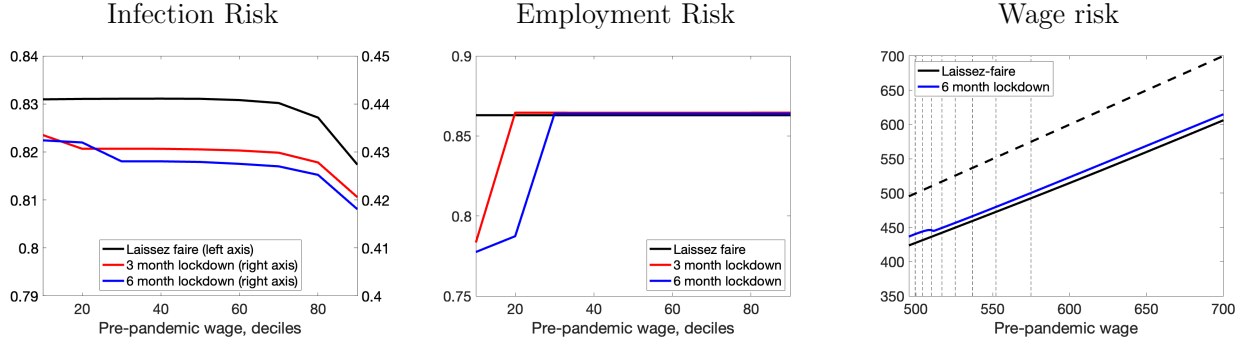
Notes: For employment and infection risk we follow workers for four months, starting one month before lockdown is implemented. Infection risk is defined as the probability a worker ever becomes infected in that period. Employment risk is defined as the share in employment at the end of the time horizon. Both of these are plotted conditioning on the decile of a worker's wage one month prior to the start of lockdown. Wage risk depicts the mean weekly wage of a worker at the peak of the pandemic against the wage they would have been earning absent the pandemic. The dashed line is the 45° line, representing no expected change in wages. The vertical lines represent deciles of the pre-pandemic wage distribution.

is room for inter-generational transfers to make lockdown policies more equitable across age groups.

In the model aging is a stochastic process and hence it is not clear a priori how severe the gains and losses from lockdown manifest themselves by age (measured in years). Figure 5 plots by age at lockdown, the probability a worker dies from Covid-19 in the next year and the proportion of time in the following year they spend in employment. For both cases we consider the same three policies as before. Although the young are more likely to become infected through increased exposure in the workplace, the higher mortality of the old dominates this effect and the probability of contracting and dying from the virus monotonically increases with age. The probability of employment by age is unimodal. For the majority of the domain, employment declines with age as a larger share of workers exit the labor market. Since we assume that, when entering the labor market at age twenty five, a worker starts their life in unemployment, employment rates increase at the start of a worker's career.

The pandemic poses a much greater threat to life for older workers. Under the laissez-faire policy approach, an eighty year old worker faces almost ten times the risk of losing their life than a twenty five year old. In addition, implementing lockdown policy reduces the probability that an older worker dies by a greater amount than for the young. Only for very old workers is there any discernible difference between the death rates under laissez-faire and a six month lockdown. Contrast that to the second panel which shows that the cost, in

Figure 5: Heterogeneous effects by age

Probability of Covid-19 death:
in one year post-lockdown

Mean proportion of time employed
over one years post-lockdown

employment, is borne by all. The reduction in employment from lockdowns attenuates in age making the youngest workers garner the least benefit, in terms of a reduction in mortality, and pay the highest cost, in terms of employment.[12]

4 Coronavirus Job Retention Scheme

The Coronavirus Job Retention Scheme, is a furlough policy that was first implemented on March 20th, 2020, six days before the first implementation of lockdown.[13] We model the policy as it was implemented at its onset. An employer can furlough its employee and claim 80% of the employee's wage from the government, capped at £2,500 per month. The employee cannot be asked to do additional work for the firm and the firm is free to contribute additional remuneration to the worker. The scheme was extended in a number of ways over the following year. Notably, it was extended to the self-employed and included an employee bonus if furloughed workers were brought back on the payroll. Since the furlough scheme and lockdown ran in unison, to understand the labor market response it is important to model both policies simultaneously.

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[12]In the limit, taking age to infinity, the differences in employment across different lockdowns will be zero, since all workers will have retired. A more sophisticated aging process with more than two age categories would show this attenuation more clearly than is apparent in Figure 5.

[13]Although introduced on the 20th of March, firms were able to make backdated claims to the start of the month.

In the model, when negotiating contracts, workers and firms jointly choose the work environment m that maximizes the joint surplus of the match. Absent furlough policy, this is a binary choice between working as normal away from home ($m = 1$) or producing less and working remotely ($m = 0$). Under the government's furlough policy, the work environment choice is now a tertiary one, where the match can also be furloughed ($m = 2$). When $m = 2$, the match sits idle, taking the transfer from the government, while the worker additionally enjoys home production as they would when unemployed. The total flow output of a match is thus given by equation (5), where $\tilde{f}(x)$ is the transfer from the government.

$$p(\alpha, x, m) = \begin{cases} g(x)\tilde{h}(\alpha) & \text{for } m = 0 \text{ and the worker works from home} \\ g(x) & \text{for } m = 1 \text{ and the worker works as normal} \\ \tilde{f}(x) + b_u & \text{for } m = 2 \text{ and the worker is furloughed} \end{cases} \tag{5}$$

For simplicity, we have assumed that the government pays the transfer to the match and it is then split according to the Nash bargaining protocol outlined previously. Under the bargaining protocol in the model, whomever receives the payment is inconsequential for how it is then divided. Further, the policy only allowed existing matches to be furloughed. Hence in the model, new jobs must start out as either $m = 0$ or $m = 1$ jobs and can only be furloughed after future negotiations. To qualify for the transfer, the job must also generate positive surplus in a world without a pandemic. To replicate the policy as closely as possible we assume that

$$\tilde{f}(x) = \max\left(0.8 \times g(x), 462.7\right).$$

The cap of 462.7 is based on the after tax weekly income of somebody earning £2,500 per month, given that the government would recoup any taxes paid back to them.[14] Finally, we assume the furlough policy starts and ends at the same time as the lockdown policy. Exposition of the extension of the model is provided in a supplementary appendix. The structure is similar to the baseline with an additional choice to furlough afforded matched agents. Results of the simulation for a six month lockdown with furlough are displayed in Figure 6.

The calibrated model suggests a large uptake in the furlough policy. The proportion of employed on furlough peaks at 54.5%, at the height of the pandemic. To put that in context, estimates from the Business Insights and Conditions Survey suggest that in the month of May, two months after lockdown was implemented, the proportion of the UK workforce on furlough was at 31.6%, see Hopson and Wilkinson (2021).

Jobs switching to furlough implies fewer workers commuting and hence a reduced infection rate. The stock of workers voluntarily working from home is small, and even smaller under a furlough scheme. However, the furloughed workers make a considerable impact on the

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[14]A gross pay of £2,500 per month, gives a weekly equivalent of £576.92. Using the UK tax calculator, from that: £67 will be paid in income tax; and £47.15 in national insurance contributions.

Figure 6: Dynamics of the pandemic and economy with furlough
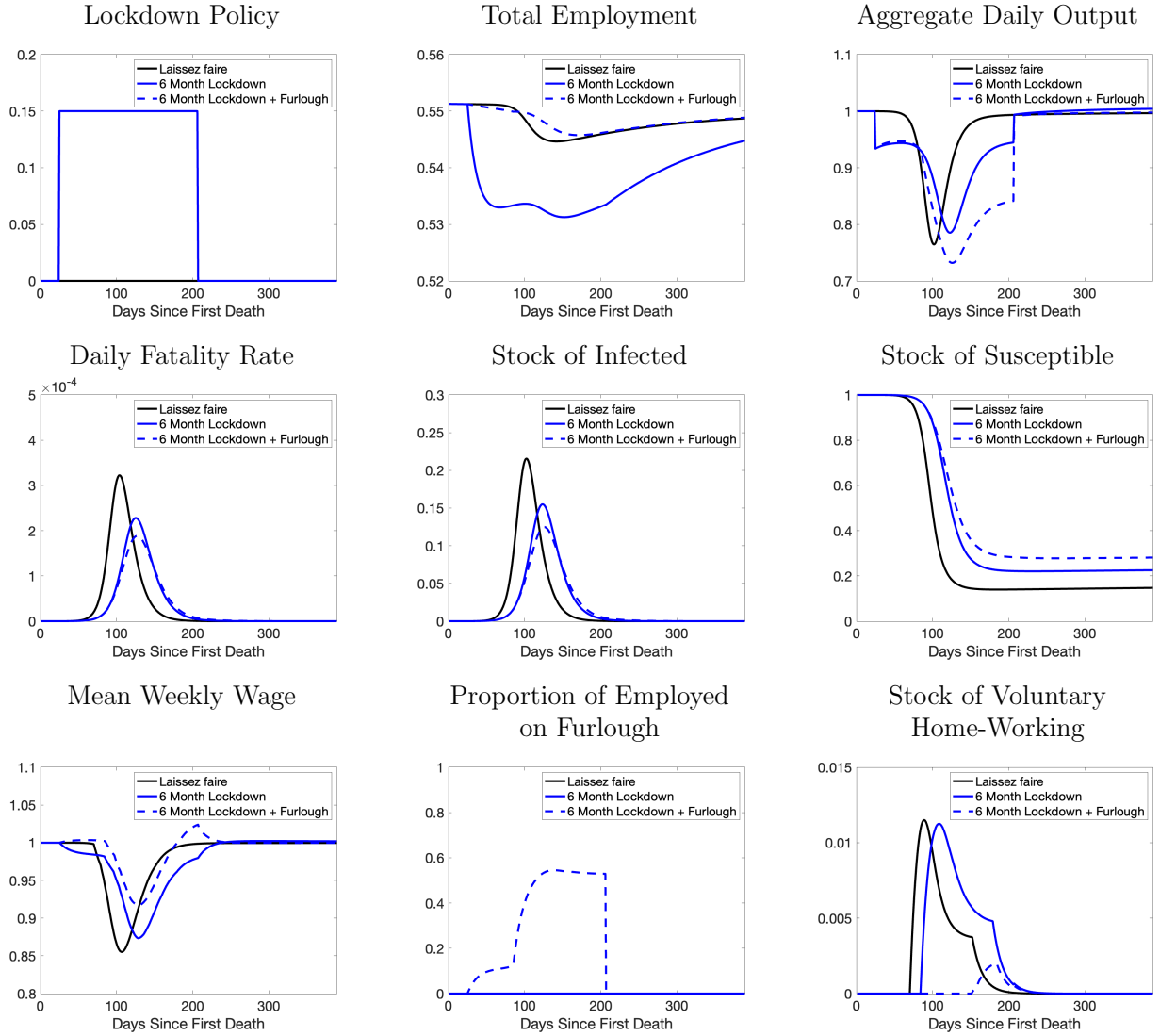
reproduction number and as can be seen by the middle panel of Figure 6, help suppress the virus and ultimately save lives. Of course, having workers sit idle will have an impact on output. While jobs are saved (upper middle panel) a large share of these workers are not engaged in production and thus output losses under furlough are higher than in a lockdown in its absence. However, these output losses are not as large as simply multiplying output by the proportion of furloughed workers, since the jobs that are furloughed are not selected at random. Rather, low productive jobs and those that require working away from home are being furloughed and thus losses in output are mitigated. This raises the interesting

Figure 7: Heterogeneous effects of furlough policy on the worker cross-section

| Infection Risk | Employment Risk | Wage risk |
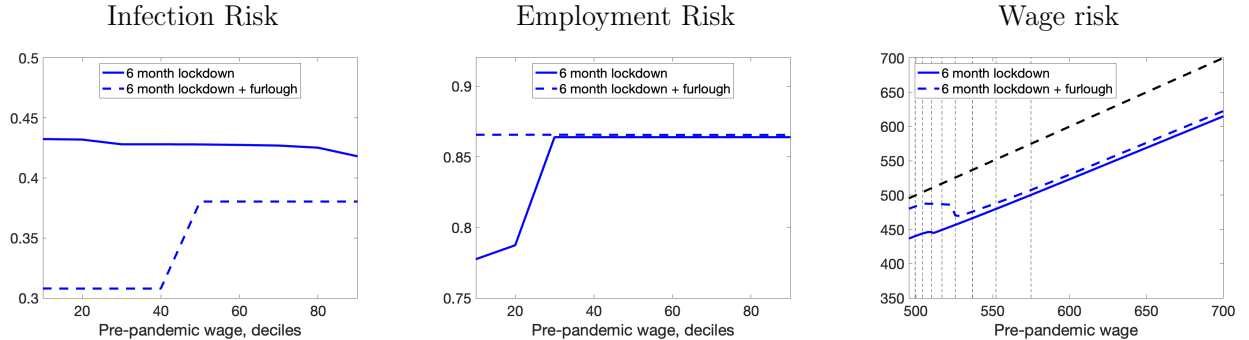
Notes: Plots are constructed as in Figure 4.

question in terms of how generous the furlough transfer from the government should be. For each additional pound spent on furlough, the marginal job being furloughed generates greater economic benefit to the country at large.

The furlough policy appears to be good for workers. It softens the fall in employment and wages over the pandemic. Note however, that unlike when comparing output, this does not take into account the large costs associated with the policy. What is clearer is which workers benefit. Figure 7 replicates Figure 4 with the inclusion of the furlough scheme. Under a standalone lockdown policy, low wage workers are more likely to get infected and face a much higher probability of job loss. Under the job retention scheme, these jobs that were laid off are now furloughed and workers across the wage distribution face the same level of employment risk. In terms of infections, risk in the aggregate is brought down and it is the previously low wage workers who gain the most. This follows, since they are largely furloughed and have a reduced Poisson rate of catching the virus — $\lambda_0 \ell_{it}$ rather than $(\lambda_0 + \lambda_1)\ell_{it}$. Finally, the furlough policy also protects the incomes of low-wage workers, keeping their peak infection wages relatively close to those they had in the pre-pandemic world.

Welfare

This section explores the welfare implications of the Coronavirus Job Retention Scheme as well as those of lockdown policies more generally. When evaluating the UK's furlough policy, the previous section gave a clear case for a benefit — mitigating the inequality induced by lockdown policies. Absent any concern for an equitable distribution, evaluating the furlough policy depends on the weight a social planner places on lives lost relative to the economic cost.

Rather than being explicit about a social welfare function, we follow Kaplan et al. (2020) and define a policy possibility frontier. This function is useful for policymakers as it plots

Figure 8: Policy possibility frontier

One year post lockdown | Two years post lockdown
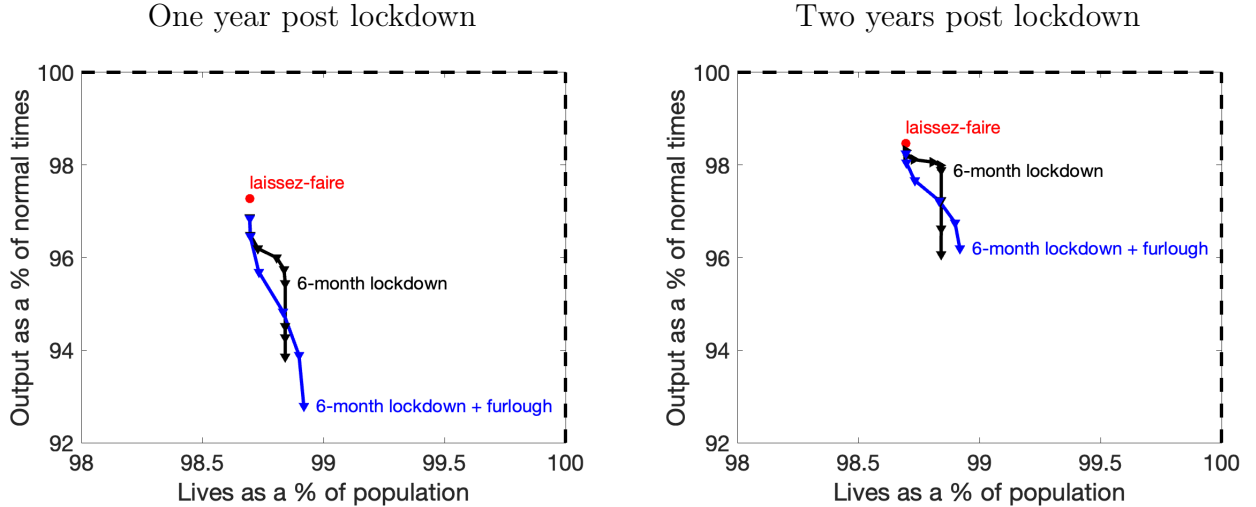
Notes: The figure plots lives lost and output loss relative to a world with no pandemic. The direction of the arrows show an increase in the duration of the lockdown policy.

the feasible outcomes, lives saved and economic consequences of different lockdown policies. Taking one and two year horizons, Figure 8 plots differing lengths of lockdown, with and without furlough, on this health-economic space. One can see the clear trade-off between health and economic costs when setting the length of the lockdown. Irrespective of the furlough policy, a longer lockdown will save more lives, but come at a greater economic cost.

There are many dimensions to lockdown and furlough policy such as when to lockdown, the strength of the lockdown and the generosity of the furlough. Figure 8 fixes all these dimensions, as has been described, to match the experience of the UK. Treating these other dimensions as fixed, a social planner could choose from an optimal policy menu by tracing the outer envelope of Figure 8. Tracing the policy menu from Figure 8 shows that, over both time horizons, a social planner who puts greater (lesser) weight on saving lives relative to output would find the furlough policy more (less) appealing.

5 Conclusion

This paper combines two workhorse models from labor economics and epidemiology to create a choice theoretic model of disease transmission and a frictional labor market. Worker-firm decisions about whether to work from home and firm's vacancy decisions are consequential for the state of the economy and crucial for the infection rate. Lockdown policy results in large economic costs borne by young and low-wage workers while primarily it is the old benefiting from the decrease in mortality. Inter-generational transfers could be implemented

to compensate young workers. Understanding the co-movement of the pandemic and labor market is crucial for policymakers especially when deciding on lockdown policies. Finally, we show that the 'Coronavirus Job Retention Scheme' implemented by the UK government equalizes the economic costs associated with lockdown across the wage distribution. Further, we show that if a social planner has sufficient concern for health rather than economic outcomes, the scheme is also *optimal* even ignoring distributional concerns.

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A   Appendix

A.1   Surplus functions of baseline model

The demography of the model has workers moving from working age to retiring to death and the health dynamics from susceptible, to infected, to recovered, conditional on survival. We present the value functions in the same order the model is solved. Starting with terminal conditions and working backwards.

Retired workers

We begin with a retired individual who has recovered from the illness. The index t encapsulates all potential aggregate state variables that vary with time. The discounted value is the sum of the flow value workers get after retiring b_o and the option value of death, which occurs at Poisson rate χ.

$$rR_{rt} = b_o + \chi(0 - R_{rt}) + \dot{R}_{rt}$$

It can be seen that this value function is independent of time and can be rewritten dropping the time subscript as

$$R_r = \frac{b_o}{r + \chi}.$$

Retired agents who are currently infected have an increased death probability of γ_o which varies with time through the evolution of the proportion of sick people. Additionally, they can recover from their illness at a rate ρ_o.

$$rR_{it} = b_o + (\chi + \gamma_o)(0 - R_{it}) + \rho_o(R_r - R_{it}) + \dot{R}_{it}$$
$$(r + \chi + \gamma_o + \rho_o)R_{it} = \frac{r + \chi + \rho_o}{(r + \chi)}b_o + \dot{R}_{it}$$

Finally, retired agents who are susceptible again die at the reduced rate χ but they can also become infected which again depends on the proportion of the population with the infection at time t.

$$rR_{st} = b_o + \chi(0 - R_{st}) + \lambda_o\ell_{it}(R_{it} - R_{st}) + \dot{R}_{st}$$
$$(r + \chi + \lambda_o\ell_{it})R_{st} = b_o + \lambda_o\ell_{it}R_{it} + \dot{R}_{st}$$

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Recovered young individuals

The value of being unemployed for a recovered individual is the sum of four terms. (i) The flow benefit b_u they get from being out of work. This encapsulates both pecuniary and non-pecuniary benefits including for example the value of leisure time and the value of home production. (ii) The option value of finding a job, from which if the surplus is positive they will get a fraction β of. Offers arrive at an endogenous rate ϕ_t to be determined later. (iii) The option value associated with retirement which occurs at exogenous rate η. (iv) The continuation value from dynamic changes to the offer arrival rate and infection rate. These four terms are represented in the Bellman equation below.

$$rU_{rt} = b_u + \phi_t\beta \int\int \max\{S_{rt}(\alpha,x,1), S_{rt}(\alpha,x,0), 0\} f(\alpha,x)d\alpha dx + \eta(R_{rt} - U_{rt}) + \dot{U}_{rt}$$

The value of being employed in a job of match (α,x) for a recovered individual in a contract (w,m) is given below. Where $w \in \mathbb{R}$ is the contractually agreed wage and $m \in \{0,1\}$, taking the value one if the worker leaves their abode to work and zero otherwise.

$$rW_{rt}(w,\alpha,x,m) = w + \delta(U_{rt} - W_{rt}(w,\alpha,x,m)) + \eta(R_{rt} - W_{rt}(w,\alpha,x,m))$$
$$+ \nu\left(\max\{\beta S_{rt}(\alpha,x,1), \beta S_{rt}(\alpha,x,0), 0\} + U_{rt} - W_{rt}(w,\alpha,x,m)\right) + \dot{W}_{rt}(w,\alpha,x,m)$$

Value of filled vacancy. The value of an employer in a match (α,x) with a recovered individual and contract (w,m) is equal to

$$rJ_{rt}(w,\alpha,x,m) = p(\alpha,x,m) - w + (\delta + \eta)(V_t - J_{rt}(w,\alpha,x,m))$$
$$+ \nu\left((1-\beta)\max\{S_{rt}(\alpha,x,1), S_{rt}(\alpha,x,0), 0\} + V_t - J_{rt}(w,\alpha,x,m)\right) + \dot{J}_{rt}(w,\alpha,x,m).$$

The flow value the firm receives is the production of the match, which will depends on whether the worker leaves their home ($m = 1$) or not ($m = 0$), net of the worker's wage w. From the firm's perspective whether a worker leaves to unemployment or to retirement is immaterial to them. Otherwise the option values are as in the case of the employed worker.

Value of surplus. Imposing free entry, $V_t = 0$, the surplus value for a match (α,x) in a contract (w,m) is derived by substituting the above expressions into equation (3).

$$(r + \delta + \eta)S_{rt}(\alpha,x,m) = p(\alpha,x,m) - b_u - \phi_t\beta \int\int \max\{S_{rt}(\alpha,x,1), S_{rt}(\alpha,x,0), 0\} f(\alpha,x)d\alpha dx$$
$$+ \nu\left(\max\{S_{rt}(\alpha,x,1), S_{rt}(\alpha,x,0), 0\} - S_{rt}(\alpha,x,m)\right) + \dot{S}_{rt}(\alpha,x,m)$$

Since $p(\alpha,x,1) \geq p(\alpha,x,0)$, it is easy to show that $S_{rt}(\alpha,x,1) \geq S_{rt}(\alpha,x,0)$. In fact:

$$S_{rt}(\alpha,x,1) - S_{rt}(\alpha,x,0) = \frac{(1-\tilde{h}(\alpha))g(x)}{r + \delta + \eta + \nu} \geq 0.$$

Therefore for brevity of notation we set $S_{rt}(\alpha, x) = S_{rt}(\alpha, x, 1)$, $J_{rt}(w, \alpha, x) = J_{rt}(w, \alpha, x, 1)$ and $W_{rt}(w, \alpha, x) = W_{rt}(w, \alpha, x, 1)$.

Infected young individuals

Infected unemployed are too ill to search for a job. Their value function is equal to:

$$rU_{it} = b_u + \rho_y (U_{rt} - U_{it}) + \gamma_y(0 - U_{it}) + \eta(R_{it} - U_{it}) + \dot{U}_{it}.$$

In addition to the flow value associated with any unemployment their option values consist of recovering and becoming unemployed and recovered, passing away in which case they get nothing, and retiring. Infected individuals are too ill to work, but receive a sick pay w, and they return to their job upon recovery. The value for the employed infected is equal to

$$rW_{it}(w, \alpha, x) = w + \rho_y (W_{rt}(w, \alpha, x) - W_{it}(w, \alpha, x))$$
$$+ \gamma_y(0 - W_{it}(w, \alpha, x)) + \delta (U_{it} - W_{it}(w, \alpha, x)) + \eta (R_{it} - W_{it}(w, \alpha, x))$$
$$+ \nu (\beta \max\{S_{it}(\alpha, x), 0\} + U_{it} - W_{it}(w, \alpha, x)) + \dot{W}_{it}(w, \alpha, x)$$

Other than sick pay, the value of employed infected accounts for the option value of recovering and going back to work, of passing away because of the infection, of exogenously separating, in which case they become unemployed infected, of retiring, and of renegotiating the terms of the contract, which can lead to match destruction.

Value of filled job. Employers in a match with infected employee produce nothing and are forced to deliver a mandatory sick payment w to the worker. Their value is equal to:

$$rJ_{it}(w, \alpha, x) = -w + \rho_y (J_{rt}(w, \alpha, x) - J_{it}(w, \alpha, x)) + (\gamma_y + \delta + \eta)(V_t - J_{it}(w, \alpha, x))$$
$$+ \nu ((1 - \beta) \max\{S_{it}(\alpha, x), 0\} + V_t - J_{it}(w, \alpha, x)) + \dot{J}_{it}(w, \alpha, x)$$

Employers have to option of renegotiating the terms of the contract at rate ν, which could lead to match destruction. A match can also be destroyed because of exogenous separation, occurring at rate δ, or because of employee death, which occurs at a rate γ_y. The match starts producing again upon worker recovery, occurring at rate ρ_y.

Value of surplus. Given free entry, $V_t = 0$, the surplus of a match between an employed and a sick employee can be written as follows:

$$(r + \delta + \eta + \rho_y + \nu + \gamma_y) S_{it}(\alpha, x) = -b_u + \rho_y S_{rt}(\alpha, x) + \nu \max\{S_{it}(\alpha, x), 0\} + \dot{S}_{it}(\alpha, x)$$

Notice that — even when the employee is infected — the match surplus could be positive, as long as the continuation value is larger than the unemployment flow. In this case, the match won't cease to exist, the employer will transfer a sick pay to the employee and wait until their recovery.

Susceptible young individuals

Susceptible individuals face risk of infection. The infection rate is function of the share of infected people in the economy, ℓ_{it}, and it depends on the employment status: it is equal to $\lambda_{0y}\ell_{it}$ for unemployed workers. Susceptible unemployed have the following value:

$$(r + \lambda_{0y}\ell_{it} + \eta)U_{st} = b_u + \phi_t\beta \int\int \max\{S_{st}(\alpha, x, 1), S_{st}(\alpha, x, 0), 0\}f(\alpha, x)d\alpha dx$$
$$+ \lambda_{0y}\ell_{it}U_{it} + \eta R_{st} + \dot{U}_{st}$$

which depends on the unemployment flow plus the option value of finding a jobs, getting infected unemployed, and retiring as susceptible. Susceptible employed differ by their job characteristics (α, x) and their contractual arrangements, (w, m), which in turn determine their rate of contagion. Employees working only from home $(m = 0)$ get infected at the same rate of unemployed workers while employees working away from home get infected at a larger rate, equal to $(\lambda_{0y} + \lambda_{1y})\ell_{it}$, where λ_{1y} governs the rate of contagion at work. The value of employment for susceptible workers reflects these differences and it is equal to:

$$(r + \delta + \nu + \lambda_{0y}\ell_{it} + \eta)W_{st}(w, \alpha, x, 0) = w + (\delta + \nu)U_{st} + \lambda_{0y}\ell_{it}W_{it}(w, \alpha, x)$$
$$+ \eta R_{st} + \nu\beta \max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\} + \dot{W}_{st}(w, \alpha, x, 0)$$

if $m = 0$, and equal to:

$$(r + \delta + \nu + (\lambda_{0y} + \lambda_{1y})\ell_{it} + \eta)W_{st}(w, \alpha, x, 1) = w + (\delta + \nu)U_{st} + (\lambda_{0y} + \lambda_{1y})\ell_{it}W_{it}(w, \alpha, x)$$
$$+ \eta R_{st} + \nu\beta \max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\} + \dot{W}_{st}(w, \alpha, x, 1)$$

if $m = 1$. Except for the infection rates, employees with different home-working arrangements have a similar value of employment: their matches are exogenously destroyed at a rate δ, they retire at a rate η and renegotiate their contract a rate ν.

Value of filled job. An employer (α, x) matched with a susceptible employee produces $p(\alpha, x, 0)$ if the employee works only from home or $p(\alpha, x, 1)$ if the employees works away from home. Imposing free entry, $V_t = 0$, the value of an employer matched with a susceptible employee is equal to:

$$(r + \delta + \eta + \lambda_{0y}\ell_{it} + \nu)J_{st}(w, \alpha, x, 0) = p(\alpha, x, 0) - w + \lambda_{0y}\ell_{it}J_{it}(w, \alpha, x)$$
$$+ \nu(1 - \beta)\max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\} + \dot{J}_{st}(w, \alpha, x, 0)$$

if $m = 0$, and equal to:

$$(r + \delta + \eta + (\lambda_{0y} + \lambda_{1y})\ell_{it} + \nu)J_{st}(w, \alpha, x, 1) = p(\alpha, x, 1) - w + (\lambda_{0y} + \lambda_{1y})\ell_{it}J_{it}(w, \alpha, x)$$
$$+ \nu(1 - \beta)\max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\} + \dot{J}_{st}(w, \alpha, x, 1)$$

if $m = 1$. Except for exogenous match destruction or worker retirement, the option values are as in the case of the susceptible employed.

Value of surplus. Given free entry $V_t = 0$, total surplus for a match in a contract (w, m) can de defined as follows:

$$(r + \delta + \eta + \nu + \lambda_{0y}\ell_{it})\, S_{st}(\alpha, x, 0) = p(\alpha, x, 0) - b_u$$

$$- \phi_t \beta \int \int \max\{S_{st}(\alpha, x, 1), S_{st}(\alpha, x, 0), 0\} f(\alpha, x) d\alpha dx$$

$$+ \lambda_{0y}\ell_{it} S_{it}(\alpha, x) + \nu \max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\}$$

$$+ \dot{S}_{st}(\alpha, x, 0)$$

if $m = 0$, and equal to

$$(r + \delta + \eta + \nu + (\lambda_{0y} + \lambda_{1y})\ell_{it})S_{st}(\alpha, x, 1) = p(\alpha, x, 1) - b_u$$

$$- \phi_t \beta \int \int \max\{S_{st}(\alpha, x, 1), S_{st}(\alpha, x, 0), 0\} f(\alpha, x) d\alpha dx$$

$$+ (\lambda_{0y} + \lambda_{1y})\ell_{it} S_{it}(\alpha, x) + \lambda_{1y}\ell_{it}(U_{it} - U_{st}) \tag{6}$$

$$+ \nu \max\{S_{st}(\alpha, x, 0), S_{st}(\alpha, x, 1), 0\}$$

$$+ \dot{S}_{st}(\alpha, x, 1)$$

if $m = 1$. Notice that for some (α, x), it might be the case that $S_{st}(\alpha, x, 0) > S_{st}(\alpha, x, 1)$. Differently than recovered, a match with a susceptible employee might optimally set $m = 0$ and produce only through home-working. In what follows, we denote $S_{st}(\alpha, x)$ the maximum of $S_{st}(\alpha, x, 0)$ and $S_{st}(\alpha, x, 1)$ for a given (α, x).

A.2   Dynamics of Baseline Model

The evolution of the measure of unemployed workers follows dynamic system given below where the first subindex denotes the health status $h \in \{s, i, r\}$ and the second the time t.

$$\dot{u}_{st} = \psi + \delta \int \int e_{st}(\alpha, x) d\alpha dx + \nu \int \int e_{st}(\alpha, x)\{S_{st}(\alpha, x) < 0\} d\alpha dx$$

$$- \phi_t u_{st} \int \int \{S_{st}(\alpha, x) \geq 0\} f(\alpha, x) d\alpha dx - \lambda_0 \ell_{it} u_{st} - \eta u_{st}$$

$$\dot{u}_{it} = \delta \int \int e_{it}(\alpha, x) d\alpha dx + \nu \int \int e_{it}(\alpha, x)\{S_{it}(\alpha, x) < 0\} d\alpha dx$$

$$+ \lambda_0 \ell_{it} u_{st} - (\rho_y + \gamma_y + \eta) u_{it}$$

$$\dot{u}_{rt} = \delta \int \int e_{rt}(\alpha, x) d\alpha dx + \nu \int \int e_{rt}(\alpha, x)\{S_{rt}(\alpha, x) < 0\} d\alpha dx$$

$$+ \rho_y u_{it} - \phi_t u_{rt} \int \int \{S_{rt}(\alpha, x) \geq 0\} f(\alpha, x) d\alpha dx - \eta u_{rt}$$

For measures of employed, we also need to keep track of their match quality (α, x) and for the susceptible whether they work at home or away from home, taking subindex zero and one, respectively. Note the total susceptible employed in match (α, x) is the sum of those employed in that match working from home and outside of the home, $e_{st}(\alpha, x) := e_{0st}(\alpha, x) + e_{1st}(\alpha, x)$.

$$
\begin{aligned}
\dot{e}_{0st}(\alpha, x) =\ & u_{st}\phi_t\{S_{st}(\alpha, x) \geq 0\}\{S_{st}(\alpha, x, 1) < S_{st}(\alpha, x, 0)\}f(\alpha, x) - (\delta + \eta)e_{0st}(\alpha, x) \\
& - \nu e_{0st}(\alpha, x)\{S_{st}(\alpha, x) < 0\} - \nu e_{0st}(\alpha, x)\{S_{st}(\alpha, x) \geq 0\}\{S_{st}(\alpha, x, 1) \geq S_{st}(\alpha, x, 0)\} \\
& + \nu e_{1st}(\alpha, x)\{S_{st}(\alpha, x) \geq 0\}\{S_{st}(\alpha, x, 1) < S_{st}(\alpha, x, 0)\} \\
& - e_{0st}(\alpha, x)\lambda_0 \ell_{it} \\
\dot{e}_{1st}(\alpha, x) =\ & u_{st}\phi_t\{S_{st}(\alpha, x) \geq 0\}\{S_{st}(\alpha, x, 1) \geq S_{st}(\alpha, x, 0)\}f(\alpha, x) - (\delta + \eta)e_{1st}(\alpha, x) \\
& - \nu e_{1st}(\alpha, x)\{S_{st}(\alpha, x) < 0\} - \nu e_{1st}(\alpha, x)\{S_{st}(\alpha, x) \geq 0\}\{S_{st}(\alpha, x, 1) < S_{st}(\alpha, x, 0)\} \\
& + \nu e_{0st}(\alpha, x)\{S_{st}(\alpha, x) \geq 0\}\{S_{st}(\alpha, x, 1) \geq S_{st}(\alpha, x, 0)\} \\
& - e_{1st}(\alpha, x)(\lambda_0 + \lambda_1)\ell_{it} \\
\dot{e}_{it}(\alpha, x) =\ & e_{0st}(\alpha, x)\lambda_0 \ell_{it} + e_{1st}(\alpha, x)(\lambda_0 + \lambda_1)\ell_{it} \\
& - \nu e_{it}(\alpha, x)\{S_{it}(\alpha, x) < 0\} - (\delta + \rho_y + \gamma_y + \eta)e_{it}(\alpha, x) \\
\dot{e}_{rt}(\alpha, x) =\ & u_{rt}\phi_t\{S_{rt}(\alpha, x) \geq 0\}f(\alpha, x) + \rho_y e_{it}(\alpha, x) \\
& - (\delta + \eta)e_{rt}(\alpha, x) - \nu e_{rt}(\alpha, x)\{S_{rt}(\alpha, x) < 0\}
\end{aligned}
$$

The measures of retired evolve as follows:

$$
\dot{o}_{st} = \eta\left(u_{st} + \int\int \left(e_{0st}(\alpha, x) + e_{1st}(\alpha, x)\right) d\alpha dx\right) - (\lambda_0 \ell_{it} + \chi)\, o_{st}
$$

$$
\dot{o}_{it} = \eta\left(u_{it} + \int\int e_{it}(\alpha, x) d\alpha dx\right) + \lambda_0 \ell_{it} o_{st} - (\gamma_o + \chi + \rho_o)\, o_{it}
$$

$$
\dot{o}_{rt} = \eta\left(u_{rt} + \int\int e_{rt}(\alpha, x) d\alpha dx\right) + \rho_o o_{it} - \chi o_{rt}
$$

Finally, the infection rate evolves as:

$$
\ell_{it} = \dot{L}_{it} - \dot{L}_t
$$

where

$$
\dot{L}_{it} = \dot{u}_{it} + \int\int \dot{e}_{it}(\alpha, x) d\alpha dx + \dot{o}_{it} \qquad \dot{L}_t = \sum_{h \in \{s,i,r\}}\left(\dot{u}_{ht} + \int\int \dot{e}_{ht}(\alpha, x) d\alpha dx + \dot{o}_{ht}\right)
$$

As discussed in the main body of the text the economy is initiated from a pre-Covid-19 steady state. That is setting the left hand side of the differential equations above and ℓ_{it} to

zero. This yields the following initial allocation. Where the superscript ss denotes steady state levels.

$$u_s^{ss} = \frac{\psi(\delta + \eta)}{\delta\eta + \eta\phi^{ss}\int\int f(\alpha,x)\{S_s^{ss}(\alpha,x) \geq 0\}d\alpha dx + \eta^2}$$

$$e_s^{ss}(\alpha,x) = \frac{u_s^{ss}\phi^{ss}f(\alpha,x)\{S_s^{ss}(\alpha,x) \geq 0\}}{\delta + \eta} = e_{1s}^{ss}(\alpha,x)$$

$$o_s^{ss} = \frac{\psi}{\chi}$$

A.3   Computational Algorithm

To solve the model we need to solve for the surplus functions denoted as $S_{st}(\alpha, x, m)$. For example, the value of a recovered individual, who will always opt to work outside of the home, yields a surplus given by

$$(r + \delta + \eta)S_{rt}(\alpha,x) = p(\alpha,x,1) - b_u - \phi_t\beta\int\int \max\{S_{rt}(\alpha,x), 0\}f(\alpha,x)d\alpha dx$$
$$+ \nu\left(\max\{S_{rt}(\alpha,x), 0\} - S_{rt}(\alpha,x)\right) + \dot{S}_{rt}(\alpha,x).$$

For this surplus function and all others we approximate the state of the economy at time t by the aggregate state vector $\Omega_t := (u_{st}, u_{rt}, \ell_{it})$ such that, for an arbitrary state Ω,

$$(r + \delta + \eta)S_r(\alpha,x;\Omega) \approx p(\alpha,x,1) - b_u - \phi(\Omega)\beta\int\int \max\{S_r(\alpha,x;\Omega), 0\}f(\alpha,x)d\alpha dx$$
$$+ \nu\left(\max\{S_r(\alpha,x;\Omega), 0\} - S_r(\alpha,x;\Omega)\right).$$

Given the surplus functions, the transitional dynamics and the free entry condition defining $\phi(\Omega)$ can be computed exactly.[15] The solution algorithm works as follows.

- Construct a grid for five state variables, (α, x, Ω), where $\Omega := (u_s, u_r, L_i/L)$

- Guess $\phi^\star(\Omega)$

  - Solve fixed point for $S_r(\alpha, x; \Omega)$
  - Solve fixed point for $S_i(\alpha, x; \Omega)$
  - Solve fixed point (jointly) for $S_s(\alpha, x, 0; \Omega)$ and $S_s(\alpha, x, 1; \Omega)$

---

[15]The omission of the continuation value $\dot{S}_{ht}(\alpha, x, m)$ could omit equilibrium effects from the model. For example, the incentive for susceptible workers to self-isolate might increase as the pandemic progresses. On the other hand, this is the opposite of the *behavioral* argument put forward by British scientists that warned that starting the lockdown earlier could lead to fatigue and less compliance later on.

- Update $\phi^\star(\Omega)$ using free entry. Return to update surplus functions.

The model is solved for 50 grid points for x and α and ten for each of the aggregate states giving $(50^2 \times 10^3) = 2,500,000$ in total. After solutions are found for surpluses and job offer arrival rates the differential equations defining the aggregate states are approximated at a daily frequency.

A.4   Home working hours and earnings

Data on home-working ability across occupations are taken from Dingel and Neiman (2020). 6-digit SOC occupations are classified by their feasibility of working at home using the responses collected by O*NET database. This information is then merged with BLS data on the number and wages of workers and aggregated using 2-digit BLS's 2018 Occupational Employment Statistics.

Figure A.4: Home working hours and earnings

(a) Home working distribution

(b) Home working and hourly wage
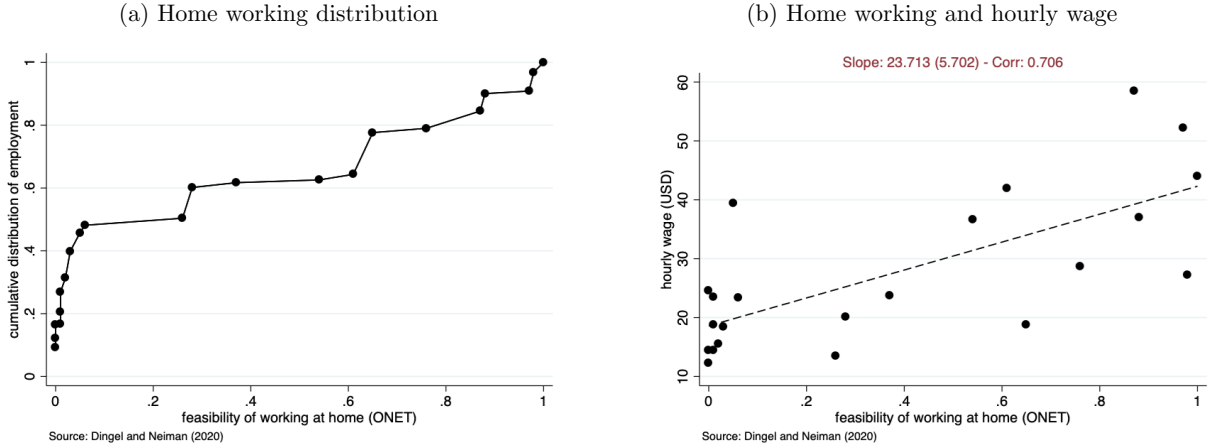

Source: Dingel and Neiman (2020)

Figure A.4 panel (a) displays the distribution of employed workers across 2-digit occupations ranked by their ability of working from home, while panel (b) scatters the hourly wage in each occupation against the same index (panel b). We exploit this data in the calibration. Specifically, we target mean and p90-p10 in the distribution of employment across home-working ability and the correlation between home-working ability and hourly wages.