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Firm behavior during an epidemic

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ABSTRACT

We derive a model in which firms operate in an epidemic environment and internalize infections among their employees in the workplace. The model is calibrated to fit the moments of the Covid-19 epidemic. We show that firms have incentives to fight against infections and can do so very effectively by increasing teleworking and rotating employees between on-site work, teleworking, and leave. The fight against infections in firms flattens the aggregate infections curve. Subsidies to teleworking reduce infections and save lives. Subsidies to sick leave reduce the cost of sick workers and raise workplace infections. Firms delay and weaken the fight against infections during economic downturns. We also consider the problem of a government that values output and lives. We show that the government prefers to severely restrict the epidemic by tolerating short-term output losses when it has a high valuation of life.

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1. Introduction

Highly infectious diseases such as the Spanish flu, the Asian flu, the Hong-Kong flu, the SARS CoV-1 and the Covid-19 tend to have a significant death toll and can cause large disruptions in economic activity. When relatively more is known regarding the role of the behavior of individuals in the transmission of these diseases (e.g., social distancing, negative externalities), less is known regarding the role of the behavior of firms. Can the behavior of firms in terms of the utilization of the workforce mitigate the transmissions in the workplace and reduce the aggregate infections and death toll of highly infectious diseases while keeping the production running?

We derive a theoretical model in which firms operate in an epidemic environment and make choices on the allocation of their employees to maximize discounted profits. The workforce of a firm is comprised of productive employees who work

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on-site and remotely, employees who are on leave/furloughed, and employees who are on sick leave. On-site employees and employees who work remotely perform tasks that are gross substitutes, and on-site employees face a higher risk of being exposed to the disease. Teleworking employees and employees on leave can catch the infection out of the workplace. The probability of infections out of the workplace depends on the stage of the epidemic and is exogenous for the firm. In addition to this risk, on-site employees face the risk of catching the infection at the workplace. The risk of an on-site employee becoming exposed to the disease is an increasing function of the number of infectious on-site employees. The firm takes this into account in its choices.

Employees with an incubated infection are infectious. As the disease progresses, they become sick with symptoms or without them. Sick employees with symptoms are on sick leave and cannot work. They either recover or pass away. Sick employees with no symptoms (asymptomatic sick) are also infectious though they necessarily recover. All recovered employees are immune to a new infection. Neither the employee nor the firm knows that the employee is infectious if the employee has no symptoms.

The firm incurs several types of costs because of infections among its employees. It pays remuneration to employees on sick leave. It also has to adjust its size because employees take sick leave and because of death among its employees. These adjustments are costly for the firm because it has a concave production function and prefers to smooth production over time.¹

In this model, strategies of the firm for reducing the infections and the associated costs include allocation of employees into teleworking and leave and their rotation between on-site work, teleworking, and leave. The employees who did not work on-site in the previous period have a lower probability of being infectious than employees who worked on-site. Therefore, the risk of infections in the workplace can decline if the firm decides to increase the share of employees who were not on-site in the previous period in its current on-site employment.

The aggregate path of the epidemic is determined in equilibrium. The firms are atomistic and do not take into account the effect of their choices on it. This generates negative externalities among firms because, if a number of them makes choices that increase infections among their employees, there will be a higher number of infectious individuals in the economy. This will increase infections out of the workplace and thus infect the employees of other firms.

We calibrate this model to match the moments of the Covid-19 epidemic, including the short timeline of vaccine development and application. We show that the fight against infections in firms has a significant effect on the dynamics of the epidemic. The choices of employee allocations and rotation in firms reduce the percentage of sick employees with symptoms at the peak by 4.8 points in the benchmark simulation exercise as compared to a (hypothetical) scenario where firms do not fight against infections. These choices also flatten the infections curve by reducing the total number of symptomatic infections about 17 percent. The death rate also declines by nearly 17 percent as a consequence.

Firms fight against infections in the workplace because that allows them to reduce their profit losses during the epidemic. The choices of firms also reduce output losses during the epidemic that stem from an increased number of employees on sick leave and death among employees. The gains of firms, however, are not as significant as gains from saved lives as measured by the value of statistical life, for example. This opens a scope for public policies.

In our simulation exercise, a 1 percent subsidy to teleworking reduces the percentage of sick at the peak of the epidemic by about 1.2 points and the total number of symptomatic infections and death rate by 5 percent. It also increases the profits of firms and their output. We also consider policies that increase sick leave payments by 1 percent, reduce these payments by 1 percent, and eliminate them. The policy that increases sick leave payments reduces infections because it increases the willingness of firms to fight against infections. This policy reduces the profits of the firms though it increases their output very marginally. On the contrary, subsidies to sick leave payments increase infections and the profits of the firms. However, they reduce output during the year when the epidemic started. Firms are almost reluctant to fight against infections if their sick leave payments are eliminated. In this case, the profits of the firms during the year of the epidemic decline very modestly by 0.06 percent, which implies a 3.93 percent lower fall in profits than in the benchmark simulation. The yearly output of firms declines by 1.37 percent because of the epidemic, which implies a 0.12 percent higher fall in output than in the benchmark simulation. In turn, we consider a policy that eliminates the costs that firms incur by paying the remuneration of furloughed employees. Such a policy motivates the firm to send some employees on temporary leave, reduce teleworking, rotate employees between on-site work and teleworking and leave and increase the rotation as compared to the benchmark. It increases the yearly profits of the firm by 0.04 percent and reduces the symptomatic infections and death toll by 2.15 percent. However, it also results in a 1.1 percent larger fall in output relative to the benchmark.²

Many countries have implemented lockdowns and imposed restrictions on production during the Covid-19 epidemic. These lockdowns and production restrictions have also often served as important motivations for policies subsidizing the costs of the remuneration of employees on leave. This paper focuses on producers and their behavior and abstracts from consumers. Admittedly, consumer behavior during the epidemic can also result in reduced demand and a fall in equilibrium output (see, e.g., [Acemoglu et al., 2021](#); [Brotherhood et al., 2021](#); [Eichenbaum et al., 2021](#)). We adopt a reduced form approach and model restrictions on production and changes in the demand as a fall in productivity which depends on the

¹ The risk of infections among employees and the risk of production disruptions because of this are an important challenge for firms according to surveys and quarterly earnings reports (e.g., see [Hassan et al., 2020](#)).

² Policies subsidizing sick leave and furlough payments have been implemented in Germany, Spain, and the US, for example.

number of sick people. We assume that as higher the number of sick people is as stronger are the lockdown, the restrictions on production, and the fall in the demand. We select the fall in productivity in a way that the resulting fall in output is 3.5 percent during the year when the epidemic started as compared to the case when there is no epidemic. This is the fall in GDP per capita in the US in 2020.

During the epidemic, the firms have to choose the allocation of infections over time. They anticipate the economic downturn, as well as the reversal and the economic upturn. It is optimal for the firm to allocate infections to the beginning of the economic downturn because the marginal product of workers is low during the downturn, a higher number of exposed workers will be recovered at the economic upturn, and a small fraction of the sick employees pass away.³ A higher number of recovered employees allows the firm to extract more gains from the economic recovery. However, this behavior of the firms increases infections in the economy and causes a deeper recession.

This fight against infections bears larger benefits for firms when there is an economic downturn than when there are no restrictions on production, lockdown, and changes in demand. The fight against infections allows firms to have 1.61 percent lower losses in terms of yearly profits and 0.46 percent lower losses in terms of output. Without this fight, their losses would be about 13 percent in terms of profits and 4 percent in terms of output.

Finally, we consider a government that acts as a planner and can choose the economy-wide allocations of workers. We assume that it values output and has a non-pecuniary valuation of life. It benefits from lower infections and death during the epidemic because the output declines as the number of sick and the death toll increase and, in addition, the death toll increases its non-pecuniary costs because of the lost lives. It takes into account the effects of its allocation of labor into on-site work, teleworking, and furlough on the aggregate path of the epidemic. The government reduces the infections and death toll by 6.6 percent more than the benchmark equilibrium when the non-pecuniary value of life is low. It adopts a “non-Covid strategy” for moderate and high non-pecuniary values of life. It reduces the infections and death toll by 48 percent more than the benchmark equilibrium when the non-pecuniary value of life is moderate. It reduces the infections and death toll by about 74 percent more than the benchmark equilibrium when the non-pecuniary value of life is high. The government implements a type of lockdown policy and allocates a very large fraction of employees to telework during the epidemic to achieve the latter result.

This paper contributes to the literature that combines epidemiological models with equilibrium behavioral choice. Studies in this literature have analyzed the role of individual choices for the dynamics of the epidemic and have emphasized the negative externality that infected individuals impose on susceptible individuals by not internalizing the costs of transmission. [Kremer \(1996\)](#) was one of the first to study this negative externality and to show that it increases infections (see also [Chen et al., 2011](#); [Toxvaerd, 2019](#)). A few studies have also considered the role of this externality in quantitative economic models of disease transmission (e.g., see [Chan et al., 2016](#); [Greenwood et al., 2019](#)). Many very recent studies in this literature investigate the Covid-19 outbreak. These studies investigate a broad spectrum of issues, such as the design of optimal containment policies and the economic effects of the implemented policies ([Acemoglu et al., 2021](#); [Alvarez et al., 2021](#); [Buera et al., 2021](#); [Eichenbaum et al., 2021](#)), the effects of testing and social distancing on the evolution of the epidemic ([Brotherhood et al., 2021](#); [Eichenbaum et al., 2022](#); [Fernández-Villaverde and Jones, 2022](#)), heterogeneous impacts of Covid-19 on the population and firms ([Alon et al., 2020](#); [Brotherhood et al., 2022](#); [Favero et al., 2020](#); [Fernández-Cerezo et al., 2021](#); [Kaplan et al., 2020](#); [Kozeniauskas et al., 2022](#); [Lee et al., 2021](#)), and its effects on the allocation of time and the labor market ([Boppart et al., 2022](#); [Kapicka and Rupert, 2022](#)).

All these studies have emphasized the importance of the behavior of individuals for the evolution of the epidemic. To the best of our knowledge, we are the first to develop an epidemiological model that takes into account the employment allocation decisions of firms. We use this model to study the trade-offs faced by firms that emerge in the epidemic, and how the resulting choices of the firms affect the dynamics of the epidemic. In our model, the firms fight against infections at the workplace. This fight reduces infections. It can thus alleviate the effects of the individual-level negative externalities. We abstract from the individual-level externalities in this model. Instead, we model negative externalities among firms assuming that they do not take into account the effect of their choices on the aggregate path of the epidemic.

There is evidence that the allocation of employment to on-site and remote work can affect the evolution of the epidemic (e.g., see [Alipour et al., 2021](#)). The identification of the quantitative importance of firms' decisions regarding changes in this allocation is not trivial because the observed changes in the places of work can be the result of the decisions of firms and employees, as well as the enacted policies. In this regard, our numerical exercises suggest that the allocation decisions of the firms play an important role for the evolution of an epidemic.

The next section introduces the model. [Section 3](#) describes our calibration strategy. [Section 4](#) presents simulation results. [Section 5](#) concludes.

2. Model

Time is discrete and runs forever. There is a continuum of identical firms of a unit measure. A firm makes choices on how to manage its workforce to maximize its discounted profits in an epidemic environment. The human resources of the

³ The disease is not particularly deadly for the working-age employees, and about 0.25% of sick pass away in the model.

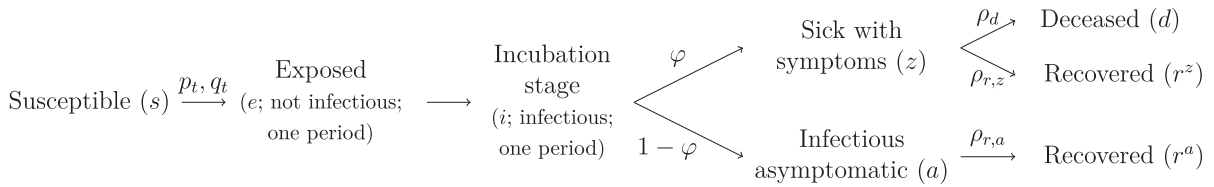


Fig. 1. Health states.

firm are comprised of productive employees who work on-site (n) and remotely (h), employees who are on leave/furloughed (ℓ), and employees who are on sick leave (z).

The production function of the firm has decreasing returns to scale and is given by

$$f(n, h) = A[\theta n^\sigma + (1 - \theta)h^\sigma]^{\frac{1}{\sigma}}, \tag{1}$$

where $A > 0$, $\alpha, \theta \in (0, 1)$, and we assume that $\sigma \in (0, 1)$ so that the tasks that on-site and teleworking employees perform are gross substitutes. The instantaneous profits of the firm at time t are given by

$$\pi_t = f(n_t, h_t) - \delta_n w n_t - \delta_h w h_t - \delta_\ell w \ell_t - \delta_z w z_t, \tag{2}$$

where $\delta_n, \delta_h, \delta_\ell, \delta_z \geq 0$, and $w > 0$ is the wage rate. The parameters δ measure the relative cost of each type of employee, and we use them to model various policies, such as subsidies to teleworking and to sick leave. The benchmark value of parameters δ is 1. The wage rate is an exogenous parameter in the model.

The firm does not anticipate the epidemic. It solves a static problem before the epidemic. It chooses n and h to maximize its instantaneous profits taking w as given:

$$\max_{n, h} f(n, h) - w(\delta_n n + \delta_h h). \tag{3}$$

Let $N = n + h$ denote the optimal employment in the firm. We assume that the firm doesn't make hiring decisions during the Covid-19 epidemic. It also does not make firing decisions even though it can keep workers on leave indefinitely.

An employee of the firm can be in either of the following states: healthy and susceptible to infection (s), exposed to infection (e), infectious with an incubated infection (i), either sick with symptoms (z) or sick without symptoms (a), and either recovered (r) or deceased (d). The exposed employees become infectious with an incubated infection in the next period. In turn, employees with incubated infection have no symptoms and become sick with symptoms or without symptoms in the next period. The exposed employees necessarily either recover or pass away. The recovered employees are immune to a new infection. Neither the employee nor the firm know that the employee is infectious if the employee has no symptoms. All these employees have an uncertain health status for the firm. Fig. 1 summarizes the health status of a worker in the model as well as its transitions.

In each period, a fraction of sick employees (ρ_d) dies and a fraction of surviving sick employees ($\rho_{r,z}$) recovers in the next period, thus, adding to the pool of deceased employees (d) and to the pool of known recovered employees (r^z),

$$d_{t+1} = d_t + \rho_d z_t, \tag{4}$$

$$r_{t+1}^z = r_t^z + (1 - \rho_d)\rho_{r,z}z_t. \tag{5}$$

Employees with uncertain health status were either working on-site or were not on-site in the previous period. We use superscript n for employees with uncertain health status who were on-site in the previous period and m for employees who were not on-site. The number of asymptomatic sick employees at the workplace and out of the workplace at time t is $a_{t,j}$ for $j \in \{n, m\}$. A fraction of them ($\rho_{r,a}$) recovers in the next period, thus, adding to the pool of recovered asymptomatic employees (r^a),

$$r_{t+1}^{a,n} = r_t^{a,n} + \rho_{r,a}a_{t,n}, \tag{6}$$

$$r_{t+1}^{a,m} = r_t^{a,m} + \rho_{r,a}a_{t,m}, \tag{7}$$

$$r_{t+1}^a = r_{t+1}^{a,n} + r_{t+1}^{a,m}. \tag{8}$$

There can be employees with incubated infection among on-site, teleworking, and furloughed employees. These employees can transmit the disease. We use $i_{t,n}$ and $i_{t,m}$ to denote the number of on-site workers and not on-site workers with incubated infection at time t , respectively.

The employees with incubated infection become sick in the next period and show symptoms with a probability $\varphi \in (0, 1)$. The number of sick employees who show symptoms is given by

$$z_{t+1} = (1 - \rho_d)(1 - \rho_{r,z})z_t + \varphi(i_{t,n} + i_{t,m}). \tag{9}$$

Table 1
The choices of the firm.

		On-Site in t	Teleworker in t	Leave in t
Uncertain status	On-Site in $t - 1$	n_t^n	h_t^n	ℓ_t^n
	Not on-site in $t - 1$	n_t^m	h_t^m	ℓ_t^m
	Recovered workers	n_t^r	h_t^r	ℓ_t^r

In turn, the number of asymptomatic sick employees is given by

$$a_{t+1}^n = (1 - \rho_{r,a})a_{t,n} + (1 - \varphi)i_{t,n}, \tag{10}$$

$$a_{t+1}^m = (1 - \rho_{r,a})a_{t,m} + (1 - \varphi)i_{t,m}, \tag{11}$$

$$a_{t+1} = a_{t+1}^n + a_{t+1}^m. \tag{12}$$

Susceptible employees who either work remotely or are on leave ($s_{t,m}$) become exposed to infection ($e_{t,m}$) at time t with a probability $q_t \in [0, 1]$. The probability of infection out of the workplace depends on the stage of the epidemic and is exogenous for the firm. The susceptible on-site employees ($s_{t,n}$) also become exposed to the infection ($e_{t,n}$) but with a higher probability. In addition to this risk, the susceptible on-site employees face the risk of getting infected at the workplace. The probability of becoming exposed to the infection when working on-site is a function of the number of infectious on-site employees, which are composed of employees with incubated infection ($i_{t,n}$) and asymptomatic sick employees ($a_{n,t}$):

$$p_t = \min \{ \Pi_{p,q}q_t + \Pi_{p,n}(i_{t,n} + a_{n,t}), 1 \}, \tag{13}$$

where $\Pi_{p,q} \geq 1$ and $\Pi_{p,n} > 0$. Parameter $\Pi_{p,q}$ captures the effect of, for example, commuting to work on the probability of infection. Parameter $\Pi_{p,n}$ measures how the infection risk increases with the number of infectious on-site workers, capturing characteristics such as workplace density and hygiene.

In each period, the firm decides how to manage workers who have uncertain health status and recovered symptomatic workers. Employees who have uncertain health status and worked on-site in the previous period have a higher probability of being infectious in the current period than employees who did not work on-site. Therefore, the firm splits workers with uncertain health status into those who did and did not work on-site in the previous period.

The firm has two groups of employees with uncertain health status and a group of known recovered employees (r). Let k_t^j denote the number of employees in group $j \in \{n, m, r\}$ who are in situation $k \in \{n, h, \ell\}$ in time period t . For example, h_t^n denotes the number of workers who have uncertain health status, worked on-site in $t - 1$, and work remotely in t . We assume that the firm cannot track the history of on-site work and being not on-site for each individual employee. Table 1 summarizes our notation for the choice variables of the firm.

We use this notation and write the number of sick on-site employees with no symptoms as the number of asymptomatic sick employees who are currently on-site and were asymptomatic in the previous period:

$$a_{t,n} = a_t^n \frac{n_t^n}{n_t^n + h_t^n + \ell_t^n} + a_t^m \frac{n_t^m}{n_t^m + h_t^m + \ell_t^m}. \tag{14}$$

Similarly, the number of sick employees with no symptoms who are not on-site is:

$$a_{t,m} = a_t^n \frac{h_t^n + \ell_t^n}{n_t^n + h_t^n + \ell_t^n} + a_t^m \frac{h_t^m + \ell_t^m}{n_t^m + h_t^m + \ell_t^m}. \tag{15}$$

The firm cannot distinguish the health status of uncertain workers. However, it can predict the number of asymptomatic workers in the workplace and out of the workplace as a function of its choices using these equations.

Employees who work on-site and are in the incubation stage at time t were exposed to infection in $t - 1$ either in the workplace or out of the workplace. The number of on-site employees in the first group is given by the fraction of employees who were on-site in the previous period and exposed to the disease on-site,

$$e_{t-1,n} = p_{t-1}S_{t-1,n}. \tag{16}$$

The number of on-site employees in the second group is given by the fraction of employees who were not on-site in the previous period and they were exposed to the disease out of the workplace,

$$e_{t-1,m} = q_{t-1}S_{t-1,m}. \tag{17}$$

Finally, the number of on-site employees in the incubation stage is given by

$$i_{t,n} = e_{t-1,n} \frac{n_t^n}{n_t^n + h_t^n + \ell_t^n} + e_{t-1,m} \frac{n_t^m}{n_t^m + h_t^m + \ell_t^m}. \tag{18}$$

An equation similar to (18) holds for the number of employees, who are not on-site and are in the incubation stage in period t :

$$i_{t,m} = e_{t-1,n} \frac{h_t^n + \ell_t^n}{n_t^n + h_t^n + \ell_t^n} + e_{t-1,m} \frac{h_t^m + \ell_t^m}{n_t^m + h_t^m + \ell_t^m}. \tag{19}$$

Finally, the number of susceptible workers who were on-site and out of the workplace in the previous period is given by

$$s_{t-1,n} = n_{t-1}^n + n_{t-1}^m - i_{t-1,n} - a_{t-1,n} - r_{t-1,n}^a, \tag{20}$$

$$s_{t-1,m} = h_{t-1}^n + \ell_{t-1}^n + h_{t-1}^m + \ell_{t-1}^m - i_{t-1,m} - a_{t-1,m} - r_{t-1,m}^a. \tag{21}$$

The firm faces the following constraints in terms of its human resources:

$$n_t^n + h_t^n + \ell_t^n = n_{t-1}^n + n_{t-1}^m - \varphi i_{t-1,n}, \tag{22}$$

$$n_t^m + h_t^m + \ell_t^m = h_{t-1}^n + \ell_{t-1}^n + h_{t-1}^m + \ell_{t-1}^m - \varphi i_{t-1,m}, \tag{23}$$

$$n_t^r + h_t^r + \ell_t^r = r_t^z. \tag{24}$$

The right-hand-side of Eq. (22) denotes the number of workers with uncertain health status who worked on-site in $t - 1$ and are available to work in t . This is given by the number of on-site workers with uncertain health status in $t - 1$ minus those who start showing symptoms in t . These workers can be allocated either into on-site work or teleworking or leave in t according to the left-hand side of Eq. (22). A similar interpretation holds for Eqs. (23) and (24).

The firm has a discount factor $\beta \in (0, 1)$ and can exist forever. It selects the allocation of employees in on-site work, teleworking, and leave for every point in time to maximize the present discounted value of its instantaneous profits. All its dynamic constraints depend on h_t and ℓ_t through the sum of both variables, $m_t = h_t + \ell_t$. This happens because teleworkers and employees on-leave face the same risk of infection, q_t . Therefore, we can write the allocation problem of the firm as a nested two-stage problem. In the first (outer) stage, the firm chooses the allocation of workers in on-site work, n_t^j for $j \in \{n, m, r\}$, and out of the workplace, m_t^j for $j \in \{n, m, r\}$, to solve the following dynamic problem

$$\begin{aligned} & \max_{\{n_t^n, m_t^n, n_t^m, m_t^m, n_t^r, m_t^r\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \pi_t \\ & \text{s.t.} \\ & (2) - (24), \end{aligned} \tag{25}$$

with $m_t^j = h_t^j + \ell_t^j$ for $j \in \{n, m, r\}$.

In the second (inner) stage, the firm allocates the employees out of the workplace between teleworking and leave in each t solving a static problem:

$$\begin{aligned} & \max_{h_t, \ell_t} f(n_t, h_t) - \delta_n w n_t - \delta_h w h_t - \delta_\ell w \ell_t - \delta_z w z_t \\ & \text{s.t.} \\ & h_t + \ell_t = m_t^n + m_t^m + m_t^r \\ & n_t = n_t^n + n_t^m + n_t^r. \end{aligned} \tag{26}$$

We assume that infections start at $t = -1$, with a small fraction $\varepsilon > 0$ of workers in the incubation stage, and that the firm could not anticipate the epidemic before $t = 0$. The initial conditions for the firm are

$$\{n_{-1}^n, h_{-1}^n\} = \arg \max_{n,h} f(n, h) - w(\delta_n n + \delta_h h), \tag{27}$$

$$n_{-1}^n + h_{-1}^n = N, m_{-1}^n = h_{-1}^n, \tag{28}$$

$$i_{-1,n} = \varepsilon n_{-1}^n, i_{-1,m} = \varepsilon h_{-1}^n, \tag{29}$$

$$n_{-1}^m = n_{-1}^r = m_{-1}^n = m_{-1}^r = d_{-1} = z_{-1} = r_{-1}^z = r_{-1}^a = a_{-1} = 0. \tag{30}$$

The time path of infection probability $\{q_t\}_{t=0}^{\infty}$ is determined in equilibrium, and depends on the number of infectious workers in the economy. At time t , this probability is given by

$$q_t = \Pi_q (\hat{I}_t + \hat{A}_t), \tag{31}$$

where $\Pi_q > 0$ is a parameter that governs the transmission rate of the disease out of the workplace, and in equilibrium

$$\hat{I}_t = i_{t,n} + i_{t,m} \quad \text{and} \quad \hat{A}_t = a_t. \tag{32}$$

Definition of Equilibrium: The equilibrium consists of time paths of labor force allocations, $\{n_t^j, h_t^j, \ell_t^j\}_{t=0}^{\infty}$ for $j \in \{n, m, r\}$, and infection probabilities $\{q_t\}_{t=0}^{\infty}$, such that:

1. Taking the sequence $\{q_t\}_{t=0}^{\infty}$ as given, firms choose labor allocations to solve problem (25) and (26).
2. The firms' choices and the law of motions give rise to the sequences $\{q_t\}_{t=0}^{\infty}$ and the distribution of workers across health states.

This model has a few notable and intuitive features. The epidemic has negative effects on the output and profits of the firm.⁴ The workforce of the firm shrinks during the epidemic because employees catch infections and take a sick leave. This reduces the output and profits since $\delta_z > 0$ and the firm cannot achieve its optimal size given by the solution of static problem (3). The workforce of the firm also shrinks during the epidemic because of deaths among workers. This also reduces output and profits. We assume that the workforce of the firm returns to its original level after the culmination of the epidemic.

The firm has incentives to increase the number of teleworking employees in times of an epidemic because that reduces the probability of infections among on-site employees, p_t , and infections among all employees given that $p_t \geq q_t$. For the same reasons, it can have an incentive to increase the number of employees on leave during an epidemic. The firm incurs losses in terms of current profits when it allocates employees into teleworking and leave but reduces future profit losses which stem from sick leave payments and adjustments in the size of the workforce. It also has incentives to rotate employees between on-site work and either teleworking or leave because employees who were working on-site previously have higher chances of being infectious than employees who were either teleworking or on leave in previous periods. All these incentives are stronger for higher values of the ratio p_t/q_t .

The choices of the firm are also influenced by the values of δ_n , δ_h , δ_ℓ , and δ_z , which we treat as policy parameters. For example, on-site work can be restricted and more costly to carry during a lockdown. We assume that lockdowns can increase the value of δ_n and that increases the costs of carrying on-site work in the firm. An increase in the value of δ_n amplifies the incentives of the firm to allocate employees into teleworking. Subsidies to teleworking have a similar effect on the incentives of the firm. We model such subsidies as a reduction in the value of δ_n . The firm does not furlough workers when $\delta_\ell = \delta_n$ since teleworking bears higher rents at the same cost. Schemes that reduce the costs of employment adjustments can be represented as reductions in the value of δ_ℓ because a lower value of δ_ℓ implies a lower cost of sending employees to leave and adjusting the size of the workforce and production. In turn, subsidies for the remuneration of employees on sick leave can be represented as a reduction in the value of δ_z . The latter two policies can reduce the costs of the firm. However, for example, a lower value of δ_z also reduces the incentives of the firm to fight infections because it reduces the cost of infections for the firm.

The firms in this model do not internalize the effect of their choices on the out of the workplace, aggregate infection q . This creates negative externalities among the firms since infection risk among employees of all firms increases if any number of firms chooses to cut back their fight against infections.⁵

3. Calibration

We interpret the model period as being one week and select a value for the time discount parameter β such that annual time discounting is equal to 0.96. We normalize the value of productivity parameter A to 1 and set $\alpha = 0.7$, which implies that the share of labor force compensation in an environment with no disease/epidemic is 0.7. We set the wage rate so that the optimal size of the firm is equal to 1 in such an environment, i.e., $N = 1$.

We choose the values for the relative productivity of on-site workers θ and the elasticity of substitution between working on-site and teleworking σ in a way that the firm chooses 5.7% of its employees to be teleworkers in a non-epidemic environment. Moreover, it chooses about 30% of its active labor force to be teleworkers at the peak of the epidemic in the benchmark equilibrium. This is in line with the evidence reported by [U.S. Census Bureau \(2022\)](#) and [Brynjolfsson et al. \(2020\)](#). [U.S. Census Bureau \(2022\)](#) reports that about 5.7% of employees were teleworking in 2019. In turn, [Brynjolfsson et al. \(2020\)](#) conducted a survey among workers in the US and found that nearly 30% of the interviewed individuals were teleworkers on April 1, 2020, but used to commute to work before the Covid-19 outbreak.⁶

The benchmark equilibrium is defined as the situation with no government policy, so that all δ parameters are equal to one. [Table 2](#) summarizes the values of all these parameters.

Regarding the parameters related to Covid-19, we set $\rho_d = 0.00248$ and $\rho_{r,z} = 0.496$ simultaneously so that the model fits an infection-fatality rate of 0.25151% ([CDC, 2022](#)) and an average symptom duration of 14 days ([Vekaria et al., 2021](#)). We assume that the average duration that an asymptomatic individuals stays infectious is the same as that of a symptomatic person, $\rho_{r,a} = \rho_{r,z}$.

The estimates of the fraction of asymptomatic individuals who caught Covid-19 are highly imprecise and range from 4% to 75% ([CEBM, 2020](#)). We set $\varphi = 0.5$, which implies that the numbers of asymptomatic and symptomatic sick individuals

⁴ The firm has positive profits because $\alpha < 1$. One way to rationalize the market structure in this model is to assume that the firms incur entry costs and profits serve to cover these costs as in [Hopenhayn \(1992\)](#) and [Melitz \(2003\)](#).

⁵ Many recent studies incorporate externalities among individuals when studying individual choices during epidemics (e.g., [Chen et al., 2011](#); [Kremer, 1996](#); [Toxvaerd, 2019](#)). In this model, we consider firms that internalize infections among their employees and choose to fight against these infections. In this sense, the firms' actions can alleviate the negative externalities among individual employees, and we focus on negative externalities among the firms.

⁶ The weekly production falls by more than 6% at the peak of the epidemic because of our choice of the values of θ and σ . This number is close to the results of [Brotherhood et al. \(2021\)](#) and [Aum et al. \(2020\)](#).

Table 2
Calibration of parameters.

Parameter	Value	Comment
Panel A. Firm		
A	1	Normalization
N	1	Normalization
α	0.7	Labor share of revenues
β	$0.96^{1/52}$	Time discount
w	0.436	Wage is such that optimal $N = 1$ in no disease/epidemic times
θ	0.516	} $\approx 5.7\%$ teleworkers in 2019 (CPS)
σ	0.9772	
δ_n	1	Policy parameter
δ_h	1	Policy parameter
δ_ϵ	1	Policy parameter
δ_z	1	Policy parameter
Panel B. COVID-19		
ρ_d	0.00248	} Infection-fatality rate (CDC, 2022)
$\rho_{r,z}$	0.496	
$\rho_{r,a}$	0.496	} Same as $\rho_{r,z}$
Π_q	0.56	
$\Pi_{p,n}$	0.726	} $\approx 50\%$ of infections in the workplace (Ferguson et al., 2006)
$\Pi_{p,q}$	1	
φ	0.5	Prop. asymptomatic, range: 4%-75% (CEBM, 2020)
ϵ	0.001	0.1% infected workers in first period

are equal in the model. We assume that the probability of an on-site employee catching Covid-19 if there are no infected on-site employees is the same as that of an employee catching Covid-19 out of the workplace, yielding $\Pi_{p,q} = 1$.

According to Ferguson et al. (2006), 70% of influenza transmissions occur outside of the household. We calibrate $\Pi_{p,n}$ so that 50% of the transmissions in the benchmark equilibrium happen in the workplace. In turn, the value of Π_q is chosen so that the basic reproduction number (R_0) of Covid-19 in our simulations is equal to 2.5. This falls within the range of the estimates of R_0 for Covid-19, from as low as 1.6 to as high as 4 (e.g., see Remuzzi and Remuzzi, 2020; Zhang et al., 2020). As an initial condition for the infection, we start with 0.1% infected workers in $t = -1$.

4. Simulations

The data about the Covid-19 epidemic and its economic impact have limitations, and wide ranges are reported for some of the available data. For example, the true fatality rates are hard to compute because infection rates in the population are not precisely known. We also know very little about infections in and out of workplaces. We have thus used a limited set of calibration targets while omitting some important dimensions. Accordingly, a word of caution is in order regarding the interpretation of our quantitative results.

We assume that the disease entirely disappears after 1.5 years. This is in line with the timeline of vaccine arrival for Covid-19. Moreover, the number of new infections becomes negligible after a year in all our firm-level simulations because of herd immunity.⁷ This implies that the firm has a static problem after 1.5 years.⁸

4.1. Benchmark equilibrium

Our benchmark simulation uses parameter values from Table 2. We present the results in the first column of Table 3 and in Fig. 2 and Fig. 3. It takes 12 weeks to the peak of infections. About 16 percent of the population is infected at the peak and 8 percent has symptoms. The disease infects 78.777 percent of the population during its course and 78.579 percent recover. The remainder pass away.

The firm puts a fight against infections. It increases the percentage of teleworking employees making it greater than 5.7%, which is the value in normal times. As illustrated in Fig. 3, these adjustments are slow at the beginning. However, the firm reacts strongly and allocates almost 30 percent of its employees to teleworking by the time infections reach their peak. The firm also starts rotating employees between on-site work and teleworking, which can be clearly seen in terms of transitions between m and n in Fig. 3.

The output of the firm declines by 1.249 percent during the first year of the epidemic as compared to the normal environment where there has been no disease. The reduction in the output is because the employees take a sick leave, teleworking

⁷ Acemoglu et al. (2021) utilize a very similar assumption regarding the length of the epidemic.

⁸ There have been several waves of the Covid-19 most notably caused by its various mutations. We can incorporate this assuming an unanticipated fall in the immunity to the disease among the recovered workers. We prefer abstracting from multiple waves in order to highlight the importance of the behavior of firms in a more basic environment.

Table 3
Benchmark equilibrium, comparative statics, and policies.

	(1)	(2)	(3)		(4)	(5)	(6)		(7)	(8)		(9)
	Benchmark	Fixed choices	Teleworking				Sick leave			Leave		
			$\theta = 0.5135$	$\delta_h = 0.99$		$\delta_z = 1.01$	$\delta_z = 0.99$	$\delta_z = 0$		$\delta_\ell = 0.1$	$\delta_\ell = 0$	
Weeks to the peak	12	13	13	13	12	12	12	13	12	12	13	
Sick at the peak (%)	8.134	12.957	6.975	6.951	8.095	8.174	12.581	8.134	7.585			
Deceased (%)	0.198	0.232	0.188	0.188	0.198	0.198	0.229	0.198	0.194			
Deceased (% Δ w.r.t. BM)	0.000	16.934	-5.034	-5.138	-0.149	0.154	15.542	0.000	-2.145			
Recovered (%)	78.579	91.886	74.624	74.542	78.462	78.700	90.792	78.579	76.894			
Recovered (% Δ w.r.t. BM)	0.000	16.934	-5.034	-5.138	-0.149	0.154	15.542	0.000	-2.145			
Production 1 year (% Δ w.r.t. ND)	-1.249	-1.384	-1.190	-1.243	-1.249	-1.250	-1.367	-1.249	-2.329			
Production 1 year (% Δ w.r.t. BM)	0.000	-0.136	0.110	0.006	0.001	-0.001	-0.120	0.000	-1.094			
Discounted profits (% Δ w.r.t. ND)	-0.155	-0.170	-0.147	-0.138	-0.156	-0.153	-0.002	-0.155	-0.153			
Discounted profits (% Δ w.r.t. BM)	0.000	-0.016	0.174	0.017	-0.001	0.001	0.153	0.000	0.002			
Profits 1 year (% Δ w.r.t. ND)	-3.834	-4.214	-3.655	-3.496	-3.868	-3.799	-0.057	-3.834	-3.794			
Profits 1 year (% Δ w.r.t. BM)	0.000	-0.396	0.353	0.352	-0.036	0.036	3.927	0.000	0.042			
Max. teleworking (%)	30.775	5.687	34.745	34.842	30.951	30.595	6.367	30.775	27.864			
Max. leave (%)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.371			
Max. n to m (%)	30.775	0.000	34.745	34.842	30.951	30.595	6.367	30.775	32.031			
Max. m to n (%)	28.907	0.000	32.927	33.026	29.081	28.729	5.866	28.907	30.209			
Sum n to m	6.962	0.000	9.830	9.888	6.966	6.912	4.172	6.962	7.581			
Sum m to n	6.832	0.000	9.683	9.712	6.837	6.784	4.141	6.832	7.443			

Note: This table summarizes our main results from simulations. Sick at the peak (%) excludes sick with no symptoms. The percentage of sick with no symptoms is equal to the percentage of sick with symptoms since $\varphi = 0.5$. Recovered (%) includes sick with and with no symptoms. Column 1 reports the results when we use the benchmark (BM) parameter values from Table 2. Column 2 reports the results when the firm does not take into account infections among its employees and does not rotate them. It keeps all employees with uncertain health status and previously working on-site n in on-site work n . It does the same for all employees with uncertain health status and previously out of the workplace m . All recovered are allocated into n and m so that the ratio of n to m is fixed and equal to the case when there is no disease. Column 3 reports the results for a 1 percentage increase in the relative productivity of teleworking employees and fixed productivity of on-site employees. This is achieved by reducing the value of $\theta = 0.5135$ and adjusting the value of $A = (\theta_{old}/\theta_{new})^{\alpha/\sigma} = 1.0035$. Columns 4–9 report the results for $\delta_h = 0.99$ and various values of parameters δ_z and δ_ℓ . BM stands for the benchmark in rows 4, 6, 8, 10, and 12. ND stands for “no disease” in rows 7, 9, and 11.

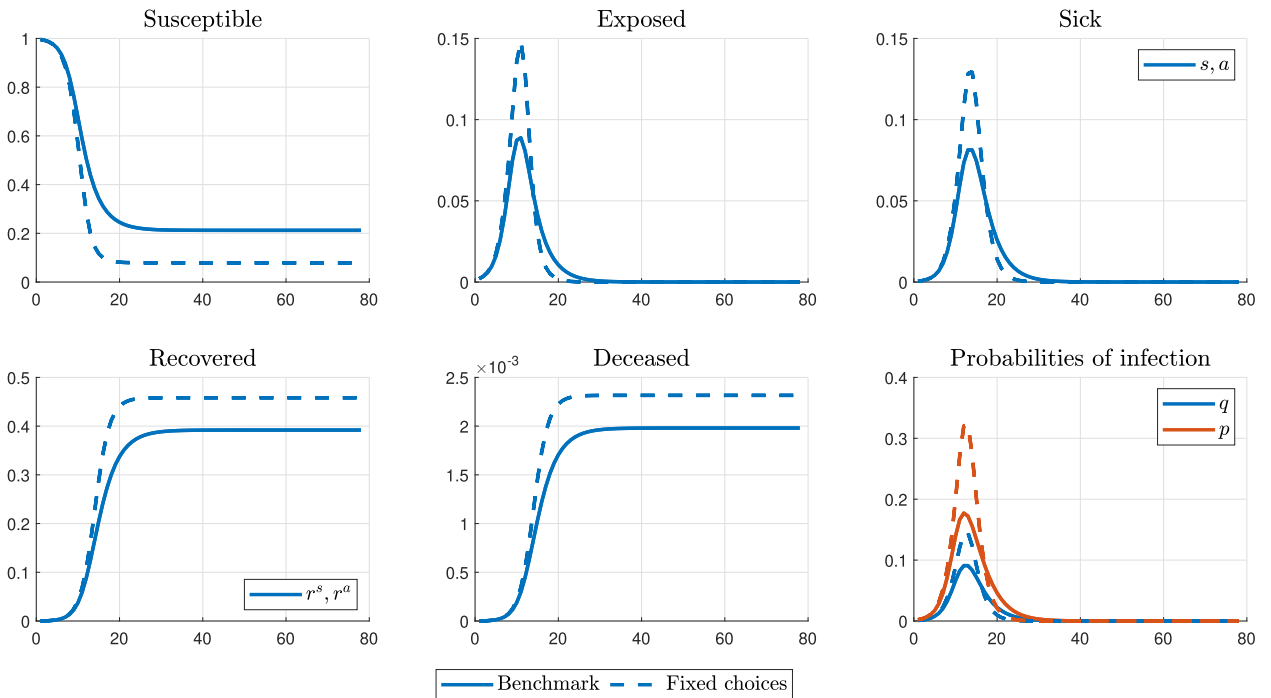


Fig. 2. The dynamics of the epidemic. Note: This figure shows the dynamics of the epidemic in the benchmark model (solid lines). It also shows the difference between these dynamics and the dynamics of the epidemic in a hypothetical scenario where the firm does not take into account infections among its employees and does not rotate them (dashed lines). It keeps all employees with uncertain health status and previously working on-site n in on-site work n . It does the same for all employees with uncertain health status and previously out of the workplace m . All recovered are allocated into n and m so that the ratio of n to m is fixed and equal to the case when there is no disease. The graphs for z and a and r^z and r^a coincide because $\varphi = 0.5$ and there are equal numbers of symptomatic and asymptomatic employees.

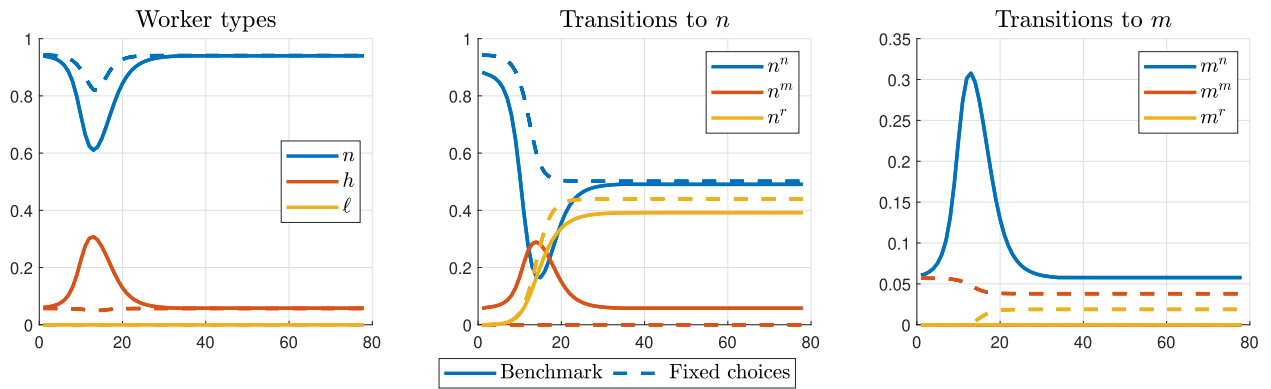


Fig. 3. The dynamics of employee allocations during the epidemic. *Note:* This figure shows the allocations of employees into on-site work, teleworking, and leave in the benchmark model where the firm takes into account infections among their employees (solid lines). It also shows the choices of the firm regarding the rotation of employees between on-site work, teleworking, and leave. It compares these dynamics with the dynamics of allocations in a hypothetical scenario where the firm does not take into account infections among its employees and does not rotate them (dashed lines). It keeps all employees with uncertain health status and previously working on-site n in on-site work n . It does the same for all employees with uncertain health status and previously out of the workplace m . All recovered are allocated into n and m so that the ratio of n to m is fixed and equal to the case when there is no disease.

is less productive than on-site work, and some workers pass away. The profits and net present value of the firm also decline as compared to the normal environment. The profits during the first year of the epidemic decline by 3.834 percent, while the value of the firm declines more modestly by 0.155 percent.

We compare these results with the results from a hypothetical scenario where the firm does not internalize infections among its employees in the workplace. In such a case, the firm does not fight against infections. It does not rotate employees and keeps all employees with uncertain health status and previously working on-site n in on-site work n . It does the same for all employees with uncertain health status and previously out of the workplace m . All recovered are allocated into n and m so that the ratio of n to m is fixed and equal to the ratio of n and m in the normal environment. Column 2 of Table 3 presents the results from the model with fixed shares of labor allocations. It takes 13 weeks to the peak of infections in this case. About 13 percent of employees are sick and have symptoms at the peak of infections, a 4.823 percentage points increase from the benchmark value. About 17 percent more employees become sick with symptoms and pass away over the course of the epidemic in the case when the firm does not fight against infections as compared to the benchmark. The choices of the firm and its fight against infections have significant effects on the dynamics of the epidemic and they flatten the infection curve.

The firm gains 0.396 percent of its yearly profits by fighting against infections in the workplace. It gains 0.016 percent in terms of the present discounted value of profits. These gains seem to be modest and there are a few reasons for that. The discounted profits are large, and the disease neither has a very long lifespan nor a very large death toll. Moreover, infections are not very persistent.

The firm's losses from increasing teleworking are exacerbated by the lower productivity of teleworking relative to on-site work, $\theta > 1/2$. In column 3 of Table 3, we consider the case when the relative productivity of teleworking employees increases by 1% but the productivity of on-site employees does not change. This is achieved by reducing the value of θ to 0.5135 and adjusting the value of A so that $A = (\theta_{old}/\theta_{new})^{\alpha/\sigma} = 1.0035$. Such a higher relative productivity of teleworking employees can be a result of, for example, the firm investing in improvements in teleworking practices and technologies and general improvements in information and communication technologies and their more widespread availability. It is less costly for the firm to allocate employees to teleworking with a higher θ and teleworking and the rotation of employees increase because of this. Profits and production also increase because of the higher value of A . The firm allocates roughly 35 percent of its employees to teleworking at the peak. The number of symptomatic infections and death during the epidemic decline by 5.034 percent as compared to the benchmark. Symptomatic infections at the peak decline by about 1 percentage point. The firm also gains 0.353 percent of its yearly profits by fighting against infections in the workplace with the higher value of A and the lower value of θ relative to the benchmark.

The gains from fighting infections can seem to be modest at the firm level in the benchmark results. The results suggest they can be significant at the aggregate level though. The fight against infections saves 0.136 percent of the GDP in the benchmark results. This implies that the gains from this fight can be at the order of 30 billion US dollars in a country like the US, where GDP in 2019 was 21.5 trillion. These gains are almost twice higher for the higher value of relative productivity of teleworking.

The fight against infections also reduces the severity of the epidemic in terms of infections and it saves lives. The latter can be important for the firms since death inflicts a cost on firms by reducing the workforce and their production. However, this is not very important for the net present value of firms. One way to gauge the economic magnitude and significance of these numbers uses the value of statistical life. According to some estimates, the value of statistical life in the US is about

\$9 million (e.g., see [U.S. Department of Transportation, 2016](#); [U.S. Environmental Protection Agency](#)).⁹ This implies that firms can save around \$1 trillion in the US by allocating employees to teleworking and rotating them. However, these benefits will not be directly appropriated by firms, which creates a scope for public policies. For example, the higher value of the relative productivity of teleworking, with fixed productivity of on-site work, implies additional lives saved and the statistical gains from that are at the order of an additional \$300 billion. The direct gains of firms in terms of profits from the higher value of the relative productivity of teleworking are much lower.

4.2. Policies

We have focused on producers and their profits and abstracted from consumer behavior and welfare in this model. In this sense, our policy exercises have a positive perspective, and we abstract from their normative implications.

Policies that encourage teleworking and discourage on-site work have been very popular in almost all countries during the Covid-19 epidemic. In the model, policies that subsidize teleworking and make on-site employment more costly for firms reduce δ_h and increase δ_n . These are similar to an increase in the relative productivity of teleworking for the choices of labor allocation of the firm. They have opposing effects on the profits though as a lower δ_h increases profits and a higher δ_n reduces them. We consider subsidies to teleworking equivalent to a 1 percent reduction in δ_h . Column 4 of [Table 3](#) presents the results. It is enough to subsidize teleworking by 1 percent to achieve significant reductions in peak infections, total infections, and death.

We consider policies that change the costs that firms incur paying remuneration to employees on sick leave. Employees that have symptoms recover with a probability of almost 1 by the sixth week in the model. In Germany, for example, firms usually pay regular wages for six weeks to employees on sick leave though they were allowed to claim back from the government their sick leave payments during the Covid-19 epidemic.¹⁰

We offer first the results from the implementation of a policy that increases the costs that the firm incurs paying employees on sick leave and sets $\delta_z = 1.01$ in column 5 of [Table 3](#). This policy reduces the profits of the firm and its value as compared to the benchmark but it improves the incentives of the firm to fight infections. The death toll of the epidemic and the total number of symptomatic infections decline by 0.149 percent as the percentage of teleworking employees and the rotation of employees between on-site work and teleworking increase. This policy also increases the output of the firm as compared to the benchmark but very marginally, 0.001 percent.

In columns 6 and 7, we consider subsidies for sick leave and offer the results from the implementation of policies that set $\delta_z = 0.99$ and $\delta_z = 0$, correspondingly. Such policies increase the profits of the firm and its value. However, they reduce the costs of having sick workers and weaken the incentives of the firm to protect its employees. Teleworking and the rotation of employees between on-site work and telework decline. As compared to the benchmark, this increases infections in the economy and the death toll of the epidemic. The firm almost does not fight against infections when $\delta_z = 0$. Such a policy significantly increases the profits of the firm during the epidemic as compared to the benchmark at the expense of higher infection rates, death toll, and lower output. Production declines during the year of the epidemic because a larger number of workers get infected and go on sick leave.

We also consider a policy that subsidizes/reduces the costs that firms incur paying the remuneration of employees on leave. Analogous policies have been implemented, for example, in Spain with the motivation to allow firms to temporarily adjust their size. We consider a policy that reduces these costs by 90 percent in column 8 of [Table 3](#). This policy has no effect on the behavior of the firm and the dynamics of the epidemic. We consider a stronger policy that completely eliminates these costs in column 9. Such a policy motivates the firm to send some employees on temporary leave, slightly reduce teleworking, rotate employees between on-site work and teleworking and leave, and increase the rotation as compared to the benchmark. It increases the yearly profits of the firm very modestly by 0.042 percent as compared to the benchmark. [Fig. 4](#) illustrates the dynamics of employee allocations in this case. All this results in 0.549 percentage points lower symptomatic infections at the peak and 2.145 percent lower total symptomatic infections and death toll during the epidemic relative to the benchmark. However, it also results in a 1.094 percent higher fall in yearly output relative to the benchmark.

4.3. Simulations with changes in A

Thus far, we have abstracted from lockdown policies, production restrictions, and changes in the demand for goods during the epidemic that can be a result of both lockdown restrictions as well as consumer behavior. In many countries, these have served as important motivations for implementing and enacting policies that subsidize the costs of the remuneration of employees on temporary and sick leave.

We take a reduced-form approach for modeling production restrictions, lockdowns, and changes in consumer demand since we do not have consumers and their demand functions in this supply-side framework. We assume that the strength of production restrictions and lockdown are positively correlated with the number of symptomatic sick people z and consumer demand is negatively correlated with it. We also assume that production restrictions and the fall in the demand during the

⁹ [Viscusi and Aldy \(2003\)](#) offer a review of the literature on the value of a statistical life.

¹⁰ Families First Coronavirus Relief Act, H.R. 6201 had similar provisions in the US.

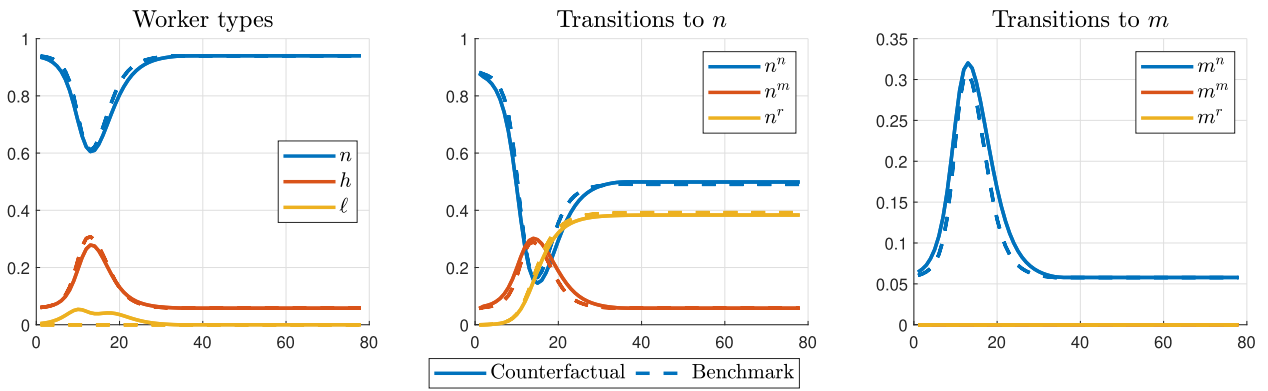


Fig. 4. The dynamics of employee allocations during the epidemic when $\delta_\ell = 0$. *Note:* This figure shows the dynamics of allocations of employees into on-site work, teleworking, and leave in the case when $\delta_\ell = 0$ (solid lines). It also compares these dynamics with the dynamics allocations of employees in the benchmark model (dashed lines).

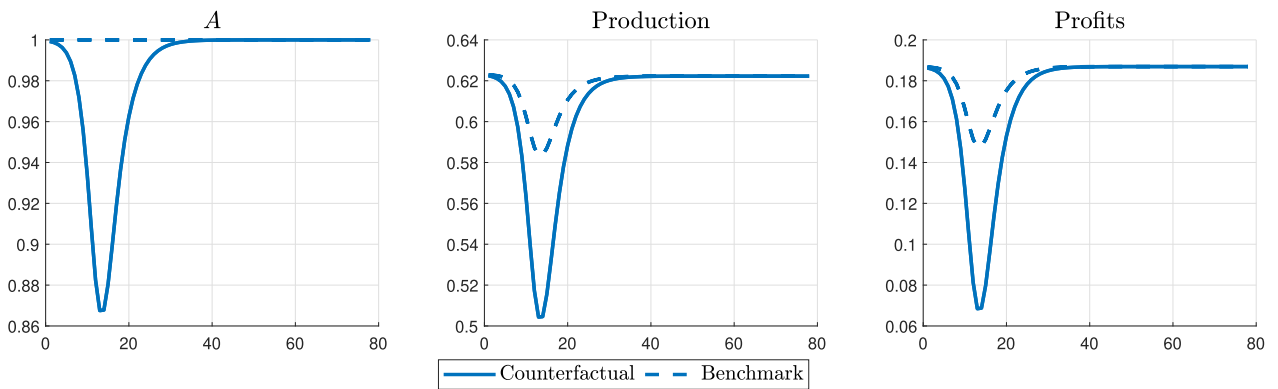


Fig. 5. The dynamics of A , production, and profits. *Note:* This figure shows our assumed dynamics of A and the resulting dynamics of production and profits (solid lines). It also shows the dynamics of production and profits in the benchmark economy where there are no changes in A (dashed lines).

epidemic because of lockdown and consumer behavior correspond to a fall in A . Finally, we assume that $A_t = 1 - \delta_A z_t$ and select the value of δ_A such that the resulting fall in output during the year of the epidemic as compared to an environment with no epidemic is about 3.5 percent.¹¹ This is the fall in GDP in the US in 2020.

Fig. 5 shows the dynamics of A , output, and profits of the firm, and Table 4 summarizes the results. According to column 1 of Table 4, the rotation of employees slightly declines because of the shock to A as compared to the benchmark in Table 3. Profits in the year of epidemic decline by 11.347 percent and output declines by 3.504 percent as compared to an environment where there is no disease/epidemic. The firm gains more from the fight against infections in terms of profits and output when there is a fall in A as compared to the benchmark. This can be clearly seen by comparing columns 1 and 2 in Table 3 and Table 4.

The disease infects about 80 percent of the population during its course. Symptomatic sick at the peak are 8.6 percent. These numbers are higher than the benchmark values in column 1 of Table 3.

The epidemic is slightly more deadly when A falls during the economic downturn because the firm cuts back its fight against infections and rotates employees less as compared to the case when A is fixed. This might seem surprising since the lower productivity of teleworkers matters less for lower values of A and the protection of workers could be less costly because the foregone revenues due to teleworking are lower.

There are a few forces that are responsible for the choice of the firm to cut back its fight against infections. A summary of the main forces is as follows. The incentives of the firm are driven by its anticipation of the trajectory of A . The static trade-off between on-site work n and teleworking h doesn't vary over time because neither the marginal revenue of n relative to the marginal revenue of h nor the relative marginal cost $\delta_n w / \delta_h w$ depends on A . Meanwhile, the marginal products of n and h simultaneously fall as A declines. This implies that the opportunity cost of having a sick worker, which is the revenue that this worker doesn't generate, changes over time. The opportunity cost of having a sick worker falls as A falls. The firm

¹¹ Fernández-Villaverde and Jones (2022) use a similar reduced form approach to model the willingness of individuals to engage in social distancing as a function of sick/death rate.

Table 4
Results for a fall in A .

	(1) Benchmark with a fall in A	(2) Fixed choices	(3) Changes in A & δ_n	(4) Leave and Sick Leave $\delta_\ell = 0$ & $\delta_z = 0$
Weeks to the peak	12	13	12	12
Sick at the peak (%)	8.621	12.957	8.278	8.979
Deceased (%)	0.199	0.232	0.196	0.205
Deceased (% Δ w.r.t. BM)	0.000	16.258	-1.456	2.682
Recovered (%)	79.037	91.886	77.886	81.157
Recovered (% Δ w.r.t. BM)	0.000	16.258	-1.456	2.682
Production 1 year (% Δ w.r.t. ND)	-3.504	-3.951	-3.469	-7.295
Production 1 year (% Δ w.r.t. BM)	0.000	-0.463	0.037	-3.929
Discounted profits (% Δ w.r.t. ND)	-0.458	-0.516	-0.460	-0.293
Discounted profits (% Δ w.r.t. BM)	0.000	-0.058	-0.002	0.166
Profits 1 year (% Δ w.r.t. ND)	-11.347	-12.771	-11.387	-7.249
Profits 1 year (% Δ w.r.t. BM)	0.000	-1.606	-0.044	4.623
Max. teleworking (%)	30.759	5.687	32.854	5.679
Max. leave (%)	0.000	0.000	0.000	29.996
Max. n to m (%)	30.759	0.000	32.854	19.961
Max. m to n (%)	28.782	0.000	30.837	18.390
Sum n to m	6.768	0.000	5.790	3.238
Sum m to n	6.643	0.000	5.702	3.162

Note: This table summarizes our main results from simulations where we consider changes in A . These changes are summarized in Fig. 5. Column 1 reports the results when we use the benchmark parameter values from Table 2 with the exception that we vary A . Column 2 reports the results when the firm does not take into account infections among its employees and does not rotate them. It keeps all employees with uncertain health status and previously working on-site n in on-site work n . It does the same for all employees with uncertain health status and previously out of the workplace m . All recovered are allocated into n and m so that the ratio of n to m is fixed and equal to the case when there is no disease. Column 3 reports the results when we change the value of δ_n . We assume that δ_n increases from 1 up to a peak value of 1.005 as A declines and reaches its minimum and it declines to its original value as A increases. We set δ_z and δ_ℓ equal to zero in column 4. BM stands for the benchmark in rows 4, 6, 8, 10, and 12. ND stands for "no disease" in rows 7, 9, and 11.

anticipates the fall in A and is reluctant to fight against infections at the beginning of the epidemic because of this. It delays sending employees to teleworking and reacts less strongly at the beginning, which increases the probability of infections at the workplace and the number of infections, exposed and sick. A high fraction of the sick employees recover since the disease is not particularly deadly. The firm also anticipates the reversal and the economic upturn and takes into account the recovery of sick employees. At the beginning of the upturn, its gains from having healthy workers start increasing. Its incentives to fight infections are also high because of the high probability of catching the disease at the workplace. These incentives are negatively affected by the "herd immunity," however.

We consider a much larger shock to A in Fig. 6 in order to illustrate these dynamics more vividly. The number of exposed and sick employees is higher at the peak because the firm has put less effort into fighting infections at the beginning of the epidemic. This leads to a higher number of recovered and immune workers later on. When the higher number of exposed and asymptotically sick employees increases the incentives of the firm to allocate employees to teleworking and rotate them, the higher number of recovered employees reduces these incentives. With the current parameterization, all these effects imply a slightly higher number of teleworking employees at the peak.

Lockdown policies can also increase the costs of on-site employment, which corresponds to an increase in δ_n . We assume that changes in δ_n are in the opposite direction to changes in A , so that δ_n increases at the beginning of the epidemic to 1.005 and declines to its original value of 1 afterward as A increases. Column 3 of Table 4 offers the results when both A and δ_n change. These changes in δ_n imply higher losses in terms of yearly profits but slightly lower losses in terms of output. The latter result holds because there are fewer infections and a lower number of workers demand sick leave in this case.

Many countries have put up an aggressive fight against the Covid-19 epidemic in an attempt to alleviate its economic impact by implementing a number of policies at the same time. In column 4 of Table 4, we consider a case when the policy eliminates the payments of the firm to all employees on leave and set $\delta_z = \delta_\ell = 0$. Such a policy considerably reduces the fall in profits. It increases the number of sick at the peak and the total infections and death toll as the firm sends employees to furlough and rotates them with on-site employees less aggressively. This policy also increases the fall in output which is now 7.3 percent. This is close to the fall in output in 2020 in many European countries, for example.

4.4. A government's problem

The governments enacted policies during the Covid-19 outbreak with the aim to reduce the economic impact of the outbreak, infections, and the resulting death toll. We consider a government that acts as a restricted planner in this section. It has the same production function as the firm (1) and faces the same outbreak and disease transmission rules (4)-(24), initial conditions (27)-(30), and parameters as in Table 2. It is a restricted planner in the sense that it decides the allocation

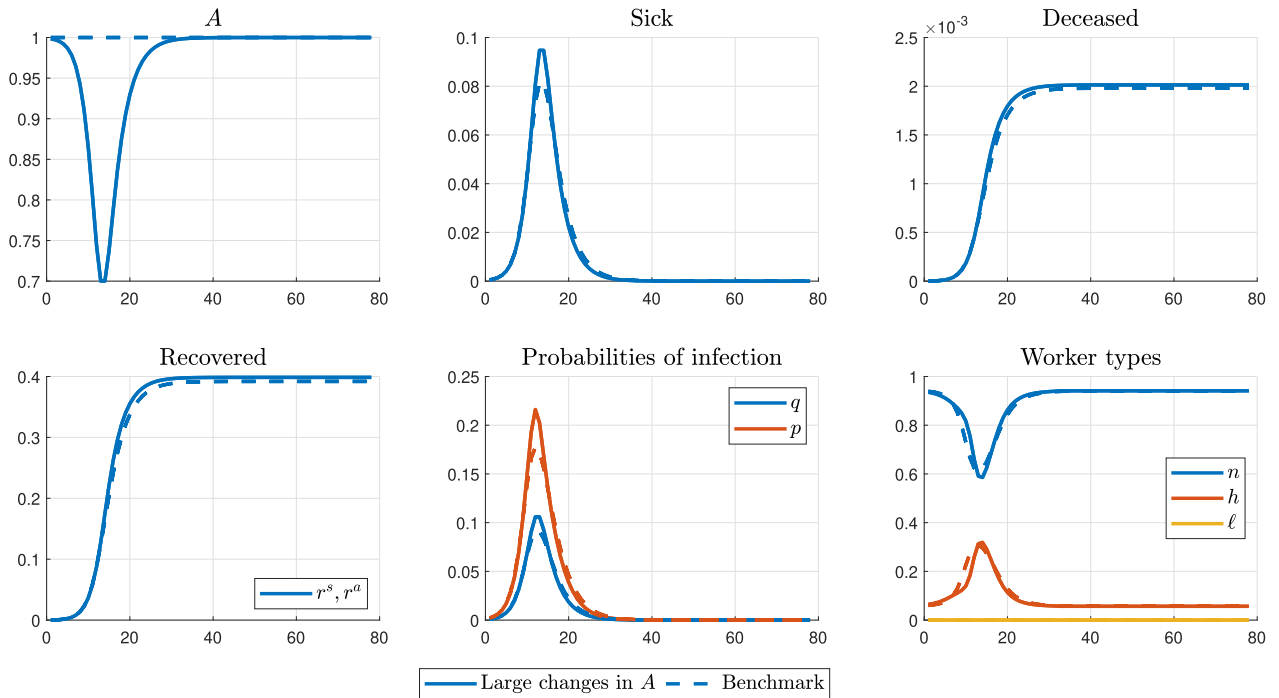


Fig. 6. Large changes in A . *Note:* We consider a relatively large fall in A (solid lines) in this figure. The figure shows the dynamics of A , sick, deceased, and recovered employees, as well as p and q and the allocations of employees into on-site work, teleworking and furlough. It compares these dynamics with the dynamics allocations of employees in the benchmark model where there are no changes in A (dashed lines). The graphs for r^s and r^a coincide because $\varphi = 0.5$ and there are equal numbers of symptomatic and asymptomatic employees.

of employees to on-site work, teleworking, and leave for the entire economy, it does not know firm-specific infections and can not affect the market structure. In contrast to the firms, it internalizes the effect of worker allocations on q_t (Eqs. (31) and (32)) and solves the following problem:

$$\begin{aligned}
 & \max_{\{n_t^s, h_t^s, \ell_t^s, n_t^m, h_t^m, \ell_t^m, n_t^f, h_t^f, \ell_t^f\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t [y_t - \delta_d (d_t - d_{t-1})] \\
 & \text{s.t.} \\
 & (1), (4) - (24), (27) - (32),
 \end{aligned} \tag{33}$$

where $\delta_d > 0$ is the government’s non-pecuniary valuation of life, $d_t - d_{t-1}$ is the number of lives lost in a period, and $y_t = f(n_t, h_t)$.¹² The outbreak is costly for the government because a higher number of sick employees reduces the workforce and output. Most of the sick employees recover and return back to the labor force. The remainder passes away. The government also incurs losses because of this in terms of the reduced output during the epidemic and in terms of non-pecuniary costs because of the lives lost.¹³ Similarly to the firm, we assume that the size of the labor force returns to its original level after the epidemic.

The differences between the government’s problem and the firm’s problem are that the government as a planner internalizes q , it has costs associated with death, and does not pay wage compensation. The government’s and firm’s problems are isomorphic when $\delta_n = \delta_h = \delta_\ell = 0$, $\delta_z w z_t = \delta_d \rho_d z_{t-1}$, and the government does not take into account the effect of allocations on q .

For facilitating comparisons, column 1 of Table 5 copies the benchmark results from Table 3. We also offer the results from a simulation where we assume that the firm internalizes the effect of its decisions on q in column 2 of Table 5. In this case, there are no externalities between firms, and the firm has more incentives to fight against infections because it knows that its choices can flatten the aggregate infection curve and smooth production over time even more. The firm puts a stronger fight against infections when it internalizes q by sending significantly more employees to teleworking and rotating them between on-site work and teleworking more aggressively. The number of infections (recovered) and the death toll decline because of this.

Column 3 offers the choices of the government for the case when it incurs zero non-pecuniary costs because of the death, $\delta_d = 0$. The government chooses to fight against infections more aggressively than the firm in columns 1 and 2. The firms

¹² The government’s problem can be written as a nested two-stage problem, similarly to the firm’s.

¹³ Acemoglu et al. (2021) consider a similar formulation for a planner’s problem with a finite planning horizon.

Table 5
Firm internalizing q and the problem of a government.

	(1)	(2)	(3)	(4)	(5)
	Benchmark	Firm internalizes q	Government $\delta_d = 0$	Government $\delta_d = 1e3$	Government $\delta_d = 1e6$
Weeks to the peak	12	12	12	14	43
Sick at the peak (%)	8.134	8.114	7.826	1.944	0.400
Deceased (%)	0.198	0.189	0.185	0.103	0.051
Deceased (% Δ w.r.t. BM)	0.000	-4.745	-6.606	-47.820	-74.280
Recovered (%)	78.579	74.851	73.388	41.068	20.283
Recovered (% Δ w.r.t. BM)	0.000	-4.745	-6.606	-47.737	-74.187
Production 1 year (% Δ w.r.t. ND)	-1.249	-3.372	-3.372	-4.245	-4.455
Production 1 year (% Δ w.r.t. BM)	0.000	-2.150	-2.150	-3.034	-3.246
Discounted profits (% Δ w.r.t. ND)	-0.155	-0.441	-0.441	-0.589	-0.815
Discounted profits (% Δ w.r.t. BM)	0.000	-0.287	-0.287	-0.435	-0.661
Profits 1 year (% Δ w.r.t. ND)	-3.834	-10.925	-10.931	-14.007	-14.819
Profits 1 year (% Δ w.r.t. BM)	0.000	-7.374	-7.380	-10.578	-11.423
Max. teleworking (%)	30.775	39.005	41.263	73.871	99.831
Max. n to m (%)	30.775	39.005	41.261	49.988	94.263
Max. m to n (%)	28.907	36.818	37.110	43.602	83.305
Sum n to m	6.962	7.112	8.196	19.695	1.040
Sum m to n	6.832	6.965	8.044	19.548	0.942
Max. q (%)	0.091	0.091	0.087	0.022	0.004

Note: This table summarizes our results from the solution of the government's (constrained planner's) problem. To facilitate comparisons, column 1 copies the benchmark results from Table 3, and column 2 offers the results from a simulation where we assume that the firm internalizes q . Column 3 reports the results from the solution of the government's problem when the non-pecuniary costs are zero, $\delta_d = 0$. Column 4 reports the results from the solution of the government's problem when the non-pecuniary costs are moderate, $\delta_d = 1e3$. Column 5 reports the results from the solution of the government's problem when the non-pecuniary costs are large, $\delta_d = 1e6$.

require subsidies equivalent to 7.4 percent of yearly profits during the epidemic to be indifferent between their choices as in column 1 and the choices of the government. In turn, columns 4 and 5 offer the choices of the government for the case when it has a moderate and high non-pecuniary valuation of life, $\delta_d = 1e3$ and $\delta_d = 1e6$. In these cases, the government adopts a no-Covid strategy. It reduces the infections and death toll by about 48% more than the benchmark equilibrium when $\delta_d = 1e3$. In turn, it chooses to allocate almost all employees to teleworking during the epidemic when $\delta_d = 1e6$. This is similar to a lockdown.¹⁴ It leads to nearly 74% lower disease transmission, infections, and death toll than the benchmark equilibrium. This is, however, at the expense of a higher fall in output. Output falls more because teleworking has lower productivity than on-site work. The firms require significantly higher subsidies to be indifferent between their choices as in column 1 and the choices of the government in columns 4 and 5. These are close to 11 percent of their yearly profits during the epidemic.

5. Conclusions

We derive a model in which firms operate in an epidemic environment and show that the choices of firms regarding the allocation and utilization of their workforce can matter for the path of the epidemic. In the model, the workforce of a firm is comprised of productive employees who work on-site and remotely, employees who are on leave/furloughed, and employees who are on sick leave. On-site and teleworking employees perform tasks that are gross substitutes, and on-site employees face a higher probability of catching the disease than employees who work remotely. Infections among employees are costly for the firm. The firm chooses the allocation of its employees into on-site work, teleworking, and leave, and rotates them to maximize its discounted profits. It takes into account how its choices affect infections in the workplace.

The aggregate path of the epidemic is determined in equilibrium. The firm does not take into account the effect of its choices on the aggregate path. This generates negative externalities among the firms.

We calibrate this model to match the properties of the Covid-19 epidemic. Our simulation results show that the fight against infections in firms has a significant effect on the dynamics of the epidemic and it flattens the infections curve. This fight bears benefits for the firms in terms of profits and output albeit these gains might not be large. Gains as measured by the value of statistical life, for example, are an order of magnitude higher, which can create a scope for public policies. In our simulations, policies subsidizing teleworking have significant effects on the dynamics of the epidemic and noticeably reduce its peak, the total number of infections, and death rate. These policies also increase the profits of firms and their output. Subsidies to sick leave payments in firms can be counter-productive and increase infections because such policies reduce the willingness of firms to fight against infections. In turn, policies reducing the costs that firms incur paying the remuneration of furloughed employees can reduce infections. However, they can also cause a deeper economic recession.

¹⁴ Many papers have found that strict lockdowns can be efficient tools for dealing with the epidemic (see, e.g., Acemoglu et al., 2021; Brotherhood et al., 2021; Glover et al., 2020).

We also simulate an economic downturn assuming that it is proportional to the number of sick people and is caused by lockdown policies, production restrictions, and changes in the demand. During an economic downturn, firms fight against infections in the workplace less because the gains from having healthy workers are low. Firms anticipate the downturn and delay allocating employees to teleworking and allow them to get exposed to the disease at the beginning of the epidemic. The number of infections, the probability of catching the disease at the workplace, and death increase because of this. On the other hand, around the end of the downturn, firms have strong incentives to fight against infections because of the high probability of infections at the workplace as well as the anticipation of the upturn, which increases the gains from this fight. The profits and output also increase more with this fight than in the benchmark.

Finally, we consider a government that acts as a (restricted) planner and chooses the economy-wide allocation of employees to on-site work, teleworking, and leave to maximize the discounted sum of output and its non-pecuniary value of life. The government chooses to substantially restrict infections by allocating a significantly higher fraction of the workforce to teleworking and by engaging in a more aggressive rotation of employees between on-site work and teleworking than the firm. It does so for low, moderate, and high non-pecuniary values of life. It adopts a no-Covid strategy for moderate and high non-pecuniary values of life. Furthermore, it implements a type of lockdown by allocating almost all employees to teleworking during the epidemic for high non-pecuniary value of life.

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