Efficient Policy Interventions in an Epidemic*

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Abstract

In the context of an epidemic, a society is forced to face a system of externalities in consumption and in production. Command economy interventions can support efficient allocations at the cost of severe information requirements. Competitive markets for *infection rights* (alternatively, Pigouvian taxes) can guarantee efficiency without requiring direct policy interventions on socioeconomic activities. We demonstrate that this is the case also with moral hazard, when the infections cannot be associated to the specific activities which originated them. Finally, we extend the analysis to situations where governments have only incomplete information regarding the values of the parameters of the infection or of firms' production.

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1 Introduction

A society hit by an epidemic is forced to face a complex system of externalities in consumption and in production. The epidemic diffuses by social contacts between agents, which are an essential by-product of production and consumption-leisure activities. Rational agents and profit maximizing firms, in this society, will take into account the individual costs of the infections generated by their choices but will not internalize the externalities of their actions. As a consequence, firms will over-produce, agents will over-consume, and in turn infections will be more widely spread.

Policy interventions will generally be necessary to design efficient mechanisms to limit infections while allowing for some economic activity. In the course of the SARS-Cov-2 epidemic the most frequently adopted non-pharmaceutical policy interventions were partial lockdowns; that is, command economy interventions directly restricting firms and agents' behavior, selecting which firms produce how much and which agents are allowed to engage in social interaction activities and how much so. In several instances, different socio-economic activities have been ranked in terms of their infectiousness and their opening staggered.

But command economy interventions are not the only possible mechanism to implement efficient allocations in general, nor are the mechanism with minimal information requirement to be implemented. As for other types of externalities, e.g., pollution, markets for the rights to externality-producing activities, or alternatively, Pigouvian taxes, can be set-up which induce agents and firms to consume and produce efficiently. The cost of infection rights or the Pigouvian taxes induce individuals and firms to limit the kinds of activities that are more likely to produce infections.[1]

An efficient Pigouvian mechanism requires firms to pay a tax proportional to the infections occurring in the workplace and, similarly, agents to pay a tax proportional to the infections occurring in the context of their consumption-leisure activities. Alternatively, this mechanism can be implemented via a system of taxes on the socio-economic activities which give rise to infections. In practice, taxes on firms' production and on individual agents' consumption-leisure activities might in fact be easier to implement than taxes directly on infections. In this case, efficient tax rates depend on the potential to spread infections and thus would be higher on firms whose production process requires close contact between workers for prolonged periods, e.g., on manufacturing firms with large assembly lines; or for firms whose abatement costs are higher, like firms relatively concentrated in dense cities whose workers, e.g., are likely to use public transportation. Tax rates would be lower instead

[1] Extensions of the welfare theorems along these lines have been pioneered by Lindahl (1919), Pigou (1920), Coase (1960), Arrow (1969), Baumol (1972); see also Bisin and Gottardi (2006) for consumption externalities due to adverse selection and Kilenthong and Townsend (2021) for pecuniary externalities.

on firms who rely more on remote working, e.g., on firms in the service, technology, and education sectors. Similarly, consumption-leisure activities like large concerts and sport events would be subject to higher tax rates. Furthermore, the tax system should include rebates based on the abatement measures that are introduced in the context of production and consumption-leisure activities, such as, e.g., mandatory testing, distancing, and use of face masks.

In this paper we study the design of these alternative mechanisms, say markets for *infection rights* or Pigouvian taxes, in the context of a simple model of a society hit by an epidemic. We determine the conditions under which these mechanisms decentralize efficient allocations in this environment. We also characterize the properties of these mechanisms. In particular, we characterize the equilibrium prices of infection rights or, equivalently, the optimal Pigouvian taxes on economic activities.

We study in detail the information requirements for the implementation of such mechanisms. We demonstrate that efficiency can be attained even when infections cannot be associated to the activities which generated them; that is, to the production choices of specific firms or to the social interaction activities of specific consumers. In this environment, the limited information on the source of the infection generates a problem of moral hazard in teams. Nonetheless, we show that the decentralization of the efficient allocation via markets for infection rights does not require this fine degree of observability at the individual level, only the observation of the average infection rate suffices. Finally, we extend the analysis to situations where governments have only incomplete information regarding the values of the parameters of the infection process or of firms' production processes. In this case efficiency cannot be attained and we compare the welfare properties of i) setting the quantity of infection rights to be traded, ii) setting their prices or taxes; iii) command economy interventions.

A few very recent papers have introduced rational, optimizing agents in the framework of epidemiological models, highlighting the importance of individual behavior in response to policy interventions and the trade-offs between health and economic costs; see e.g., Acemoglu et al. (2020), Alvarez et al. (2020), Argente et al. (2020), Atkeson (2020), Bisin and Moro (2020), Eichenbaum et al. (2020), Farboodi et al. (2020), Toxvaerd (2020). In particular, Rowthorn and Toxvaerd (2020) provide a theoretical analysis of taxes and subsidies which decentralize efficient allocations in an epidemiological model of the dynamics of an infection. Kaplan et al. (2020) provide a quantitative analysis of the distributional effects of taxes on production and consumption activities that generate infections. Also, Bethune and Korinek (2020) provide a quantitative assessment of the individual and social cost of infections. The novelty of our analysis relative to this work consists in our emphasis on the characterization of the informational requirements of measures that do not rely on the direct control of some individual choices but rather on the design of additional markets (or taxes) which can induce agents to internalize the social costs of their behavior.

Extensive previous work along these lines has concentrated on other externalities, notably pollution; see for instance, Dales (1968) and Van den Bergh (2002). The case of the externalities arising in an epidemic is distinct from those typically considered in analyses of pollution rights in that i) infections occur in and affect both the production and the consumption-leisure side of the economy; hence prices of rights or taxes implementing efficient allocations need to be designed to affect both the production choices determining the supply of goods and the consumption-leisure choices which influence the demand for various kinds of goods; and ii) infections have direct and immediate negative effects, in terms of labor lost and disease, on both firms and agents, who then partially internalize the negative consequences of their behavior even with no markets for rights nor Pigouvian taxes. As a consequence, for instance, we show the Pigouvian taxes on firms are designed so that they internalize the additional marginal benefits of infection abatement measures (beyond those on firms' output level), such as the lower costs for the public health system and the higher utility of workers' due to their improved health status. Similarly for the tax levied on each consumer, which reflects the additional costs - in terms of output loss and health expenses - of the consumer getting infected because of his/her social interaction choices, as well as the costs induced by the transmission of his/her own infection to other agents. Especially when allowing for heterogeneity in technologies and consumers, the characterization of these taxes offers novel and interesting insights, as it must reflect the variety of effects resulting from the rich web of interactions between the different kinds of production and the consumption-leisure choices of different individuals.[2]

The abstract nature of the paper does not lend itself easily to the evaluation of specific public health policy proposals, besides suggesting the general consideration of economic incentives, via taxes and markets for rights, alongside direct interventions, via e.g., selective lockdowns. It is noteworthy that an efficient system of Pigouvian taxes would include i) subsidies on abatement measures in firms and on the use of protective equipment, like masks, and protective behavior, like social distancing, testing, vaccination, that limit infections and their spread; ii) taxes on production and consumption-leisure activities; as well as iii) lump-sum transfers to all agents and firms, to rebate to them the cost of those externalities that are non pecuniary (as, for instance, the disutility of getting infected).

Importantly, we consider an environment where firms are required to provide full insurance of workers in the labor market, in that they receive full wages indepen-

[2]Our analysis is meant to apply to general epidemics, where infections are generated by the production activities of firms and the consumption-leisure activities of agents. The dimensions of heterogeneity in technology and agents' characteristics which matter are instead specific to the epidemic that is considered; e.g., accounting for demographic factors and the social interacton dimension of the production processes is fundamental for the SARS-CoV-2 epidemic.

dently of whether they are healthy or infected (and hence do not work). This induces firms to internalize the costs of infections occurring in the workplace, given by losses of productivity, but also to bear these costs for the infections that are instead the result of workers' social interaction choices. The combination of these taxes, subsidies, and transfers might then configure, for instance, a labor market where firms' abatement measures include leaving a fraction of the workers at home - thereby limiting infection and saving on taxes - without consequences on the workers' budget constraint. The most interesting implications in terms of public health policy proposals obtain when we allow for heterogeneity in the firms' and the agents' characteristics. In that case we find that the same tax rate on infections at work applies to all types of firms, no matter how important their sector is in the production system, nor how different is the cost of reducing these infections for the different firms[3]. In contrast, to control the infections generated by the agents' consumption-leisure activities it does not suffice to impose a common tax on individuals for the infections generated by such activities; personalized taxes are needed, to reflect the differences in health treatment costs and in wealth across agents, as well as in the levels of centrality or influence of consumers in the system of social interactions in the society.

2 Economy

We describe a simple abstract society hit by an epidemic.

Agents. The society is populated by H ex-ante identical (representative) agents and F identical (representative) firms. Each agent supplies labor inelastically and receives utility from consumption of a private good c and from his/her level l of social interaction activities. The agent can be infected at work or while interacting socially. Let I_l denote the probability he is infected with his/her social interaction activities. We assume I_l increases with the agent's level of l as well as with the average value of l in the population, $\bar{l}$:

$$I_l = \delta(l, \bar{l}), \text{ with } \partial\delta/\partial l > 0, \ \partial\delta/\partial\bar{l} > 0, \ \partial^2\delta/\partial l\partial\bar{l} \geq 0.^4$$

Similarly, we denote by I_w the probability he is infected at work, which is determined, as explained below, by the choices of the firm employing the agent. To simplify the analysis which follows we postulate, with a slight abuse but no essential loss of generality, the overall probability I an individual is infected is simply given by[5]

[3] Of course, the amount of the total tax paid will still vary across firms, reflecting the varying degrees to which the different processes of production are likely to generate infections.

[4] We allow so for the possibility, but do not require, that agents' social interaction choices are strategic complements.

[5] This can be formally justified if we think of the infection process developing over time, according to a Poisson process with independent arrival rates of the two kinds of infection.

$I_l + I_w$.

The representative consumer's utility function is

$$u(c, l) - \beta I,$$

with $u(\cdot)$ increasing and concave and β constituting the agent's disutility of becoming infected (for a given level of health treatment, as specified below by η).

Firms. The representative firm produces the private consumption good with the production function

$$Y = AL(1 - I)$$

where Y is output, L is the quantity of labor employed in the firm and LI is the number[6] of workers in the firm who become infected and are then assumed to be unproductive.

The probability that a worker is infected at work is given by

$$I_w = \gamma(1 - a),$$

where $\gamma > 0$ and a denotes social distancing and other abatement measures the firm can employ, at costs $C(a, L)$ (increasing and convex in a, L), to reduce infection at work of all workers employed.

Public sector. Infections need be treated by the health care sector, which we assume is public and run by the government. Public expenditures in health care are[7]

$$g = \eta(I_l + I_w)H,$$

and are financed by lump-sum taxes T levied on consumers.

We consider first the allocations and infection levels obtained at a competitive equilibrium of the economy described above, where firms hire workers at the given market wage ω and agents use their (wage and profit) income to purchase the consumption good sold by firms.[8] We assume firms must pay each worker a wage ω,

[6] Strictly speaking, the expected number.

[7] This specification assumes the cost of treating an infected individual is equal to η, independent of the size of the infected population. The analysis could however be easily extended to the case where η is increasing in I, to capture congestion and other forms of stress on the health system. The same applies to the case where η, instead of being exogenous, is a choice variable, that captures the level of treatment and in turn affects the agents' utility cost β of getting infected.

[8] The consumption good is assumed to be the numeraire.

whatever his/her health status, thus effectively providing him full insurance against the risk of getting infective and hence unproductive[9].

Competitive Equilibrium *At a competitive Equilibrium, i) each agent maximizes his/her utility, by choice of* c, l*, for given* $\pi, I_w, \omega, T, \bar{l}$ *subject to the budget constraint* $c = \frac{F\pi}{H} + \omega - T$*; ii) each firm maximizes profits* $\pi = Y - \omega L - C(a, L)$ *by choice of* a, L, Y *for given* ω, I_l*; iii) the government balances its budget; iv) markets clear; v) the externality in social interaction satisfies the consistency condition,* $l = \bar{l}$*.*[10]

Both consumers and firms face a direct disutility from the infections generated by their social interaction and their production and abatement decisions. A higher level of social interaction activity l in fact increases the probability of infection I_l resulting from such activities and this in turn generates a higher disutility for the individual βI_l. Similarly a firm, by lowering its abatement measures, saves on costs but also suffers losses because the increase in I_w induced by the reduction in a reduces the fraction of its workers who are productive[11]. But social interaction activities and abatement decisions also give rise to externalities faced by the society in an epidemic: i) each consumer does not take into account the fact that his/her social interactions also increase the probability that other individuals are infected, via the effect of his/her choice on $\bar{l}$ and hence on $\delta(l, \bar{l})$;[12] ii) he/she also does not consider the fact that this activity negatively affects the firms' productivity, by reducing the fraction of productive workers; iii) furthermore, the consumer ignores that infections entail another cost for the society, given by the health costs η incurred by the government to cure infected agents. Analogously, in the production sector, each firm does not consider the fact that: iv) agents infected at work face a utility costs β and v) also produce a societal health cost η.

Due to these externalities, competitive equilibria are not efficient. *Efficient allocations* are those which maximize *social welfare* subject to resource feasibility and the equations governing the infection process $I_l = \delta(l, l)$, $I_w = \gamma(1 - a)$. In our simple economy social welfare coincides with the representative agent utility, $u(c, l) - \beta(I_l + I_w)$, and hence the economy admits a unique efficient allocation. The efficient allocation induces an efficient level of infections in the society $(I_l + I_w) H$, which is lower than the level of infections at the competitive equilibrium.

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[9]This implies firms are affected by their workers' health status and hence internalize some of the effects of their abatement choices. As discussed below, if firms were paying workers only when healthy additional externalities arise and hence higher taxes are needed to internalize them.

[10]All complete formal definitions are in the Online Appendix.

[11]Recall this is costly for the firm given our assumption the firm needs to pay the wage to workers whether or not they are infected.

[12]This externality would be partially internalized if preferences were allowed to display an altruistic component (as, e.g., in Toxvaerd, 2021).

3 Market Implementation of the Efficient allocation

In this section we show how the efficient allocation can be implemented via markets, designed to induce firms to produce, and consumers to choose social interaction activities, efficiently.

We shall discuss several different implementation mechanism, but it is convenient to set *markets for infection rights* as the benchmark.

3.1 Markets for infection rights

The institutional market design is as follows:

Each agent engaging in social interaction activities is mandated to buy a right per unit of probability of infection I_l induced by his/her activities;

Each firm producing Y units and choosing abatement a is mandated to buy a right per unit of probability of infection I_w of each of its workers induced by its own choices.

Let q_l denote the price of these *infection rights* for social interaction activities and q_w the price of *infection rights* for production.[13]

Competitive equilibrium with infection rights. *A competitive equilibrium with infection rights is a competitive equilibrium as previously defined but i) agents and firms face the cost of infection rights, respectively $q_l I_l$ and $q_w I_w L$ in their budget constraints and profits; ii) the government chooses the supply of infection rights Q_l, Q_w and its revenue is augmented by the value of those rights; iii) markets for infection rights also clear, $I_w H = Q_w,\ I_l H = Q_l$.*

It is now straightforward to prove that, conditionally on the government supplying tradable infection rights Q_l, Q_w in an amount equal to the efficient level of infections, while letting prices clear these markets, the efficient allocation obtains at a competitive equilibrium.

Proposition (Efficiency of equilibria). *Suppose the government chooses a supply of infection rights Q_l, Q_w equal to the efficient infections $I_l H, I_w H$. Then the efficient allocation obtains at the competitive equilibrium with infection rights.*

[13]Notice that this institutional design of markets for infection rights requires that the individual probability of getting infected is publicly observable, as well as whether an infection occurs at work or via his/her social interaction activity. We shall relax this assumption in Section 4.2, when we discuss how to extend our analysis to allow for various informational asymmetries regarding infections.

The proof of the above decentralization result is by construction. That is, we find prices q_l, q_w, such that the levels of consumption and social interaction c, l chosen by individual consumers, the levels of production and abatement Y, a chosen by firms and the induced infection rates I_l, I_w, are efficient. The revenue that is generated by the sale of the infection rights is then used to fund the health expenditures incurred by the government, with the difference between the two set equal to a lump sum tax - or transfer if negative - T on consumers. The key step in the argument of the proof is then the characterization of the values of these prices and transfers, stated in the following (and proved in the Appendix):

Proposition (Efficiency of equilibria - prices)**.** *At the Efficient Competitive equilibrium with infection rights, the prices of the rights q_w and q_l are, respectively,*

$$q_w = \frac{\beta}{\partial u/\partial c} + \eta. \tag{1}$$

$$q_l = (\eta + A) + (\eta + A)\Delta + \frac{\beta}{\partial u/\partial c}\Delta \tag{2}$$

where $\Delta = \left[\frac{\partial\delta(l,\bar{l})/\partial\bar{l}}{\partial\delta(l,\bar{l})/\partial l}\right]_{\bar{l}=l}$ is the multiplicative effect of each agent's choice l on other agents' infections (via the effect on the average value $\bar{l}$), evaluated at the equilibrium $\bar{l} = l$. Furthermore, the lump-sum tax T is negative:

$$T = -I_l L(q_l - \eta) - I_h L(q_w - \eta). \tag{3}$$

The expressions of the prices of infection rights q_l, q_w allow to clearly see how the various kinds of externalities described in the previous section can be internalized by markets for those rights. The price of the rights for the firm, q_w, is equal to the marginal cost of infection for individuals (expressed in units of the consumption good) $\frac{\beta}{\partial u/\partial c}$, plus the marginal costs for the health care system η. The additional marginal cost of an infection at work, given by the decrease in the productivity of the workforce, does not enter the price of infection rights q_w because it is already internalized[14] in the firm's production and abatement decisions. Turning then to the price of the rights for the agent, q_l, we see it is composed of three terms. The first, $\eta + A$, represents the marginal costs of an infection for the health care system and for the firms (as a productivity loss). The second and third terms capture the additional

[14]This is due to our assumption that firms must pay ω to workers also when infected. If this were not the case, the price of rights for firms would have to be increased to internalize this other effect. Also, to attain efficiency lump sum transfers would have to be contingent on workers' health status.

marginal costs due to the externality in infections, generated by the effect of each agent's social interaction choice l (which determines the average value $\bar{l}$) on other agents' infections . In particular the second term, $(\eta + A)\Delta$ encodes the component of these additional costs borne by the health care system and the firms, while the third term, $\frac{\beta}{\partial u/\partial c}\Delta$, encodes the component given by utility costs of infected agents.

Finally, the revenue raised by the government at equilibrium by the sale of infection rights at prices q_l, q_w is higher than the costs borne by the health care system. This is due to the fact that, as explained above, the prices of infection rights at an efficient equilibrium do more than just allow consumers and firms to internalize the health costs of infections, that are borne by the government; they also internalize production costs and nonpecuniary costs as the utility loss due to infections. The surplus for the government is then rebated back to consumers through the lump-sum subsidy $-T$ (a negative lump-sum tax in our notation), to support the efficient allocation.

3.2 Other market implementation mechanisms

Some subtle and important issues arise in the design of markets for infection rights. We discuss here some alternative market mechanisms which implement the efficient allocation.

Market for infection rights and insurance. In the design of markets for infection rights introduced in the previous section, what is priced is the probability of being infected. But this mechanism is equivalent to one where i) agents and firms are required to buy infection right only if they and their workers, respectively, are infected; but ii) markets exists to ex-ante insure this risk, at fair prices $q_l I_l$ and $q_w I_w L$, respectively, for agents and firms.

Markets for infection rights - price-setting. An alternative policy design for the same structure of markets is given by the government setting the prices of these rights at a given level and standing ready to supply the amount requested at these prices by consumers and firms. If prices q_w, q_l are set at the level given by (1), (2), the efficient allocation is again implemented.

Pigouvian taxes. An alternative interpretation/implementation of markets for infection rights consists in the introduction of a Pigouvian tax scheme. The case in which taxes are levied directly on the infections generated by firms' and agents' choices is just a simple reformulation of the requirement to acquire infection rights. In that case, the tax rates simply coincide with the prices of rights.

Pigouvian taxes - on production and consumption-leisure activities. More interesting is the case of a Pigouvian tax on the activities generating infections. In this case, the base of the mechanism is the social interaction activity of each agent and the production of each firm, with rebates based on the firm's abatement choices.

4 Informational requirements for efficiency

In this section we argue that *markets for infection rights (and hence Pigouvian taxes) are generally superior to command economy interventions*, in that they require less information to be implemented. To this end, we study the informational requirements necessary to achieve efficiency in a society hit by an epidemic. We compare the informational requirements necessary for command economy interventions with those necessary to implement markets for infection rights. We also compare the relative informational requirements associated to the different institutional designs of markets for infection rights we discussed.

Command economy interventions require information on the technology of firms, the preferences of agents and the infection process; notably, on the productivity parameter A, the abatement cost function $C(a, L)$, the infection at work spread parameter γ, the agents' utility function $u(c, l)$ and the parameter β describing the individual disutility of infection, the infection in leisure function $\delta(l, \bar{l})$, and the health cost parameter η. The decentralization result through markets for infection rights requires instead the government to choose the efficient supply of infection rights, that is, "the supply of infection rights Q_w, Q_l corresponding to the resulting infections $I_w H, I_l H$ at the efficient allocation". In the simple environment we considered in the previous sections, the informational requirements of determining this level of the supply are not too different from those of implementing command economy interventions. The advocated *superiority of introducing markets for infection rights over command economy interventions* rests mostly on the consideration of richer and more complex economies, where agents and firms are heterogeneous and/or the values of preferences and productivity parameters are only privately known.[15] In the next sections, we extend the analysis to such richer environments and discuss the associated informational requirements.

4.1 Heterogeneity and multiple sectors

Consider first adding technological heterogeneity to firm production. In particular, suppose each firm $f = 1, 2, \ldots, F$ is characterized by different technological parame-

[15] If instead social welfare is represented by direct preferences over the public health conditions of society, the decentralization of the *efficient* allocation requires *no information* on the parameters of the economy on the part of the policy maker.

ters A_f, γ_f, for production and infection at work, and different abatement cost functions $C_f(a, L)$. In this case, command economy interventions can still implement the efficient allocation, whose definition is aptly and straightforwardly extended. But they require policy makers to set distinct production, labor demand, and abatement levels Y_f, L_f, a_f for each firm f. In other words, the policy maker needs knowledge of each firm's type f and its technological configuration $A_f, \gamma_f, C_f(a, L)$. The implementation of markets for infection rights, on the other hand, only requires the knowledge of the distribution in the economy of the configurations $A_f, \gamma_f, C_f(a, L)$, in order to determine the level of the total supply of rights for infection at work, a much smaller requirement.

The next is a fundamental but easily shown point. At the competitive equilibrium with infection rights all the different firms will be required to trade infection rights, but there is a single market for infection rights for firms and the price of such rights q_w remains determined as in (1).[16] Indeed, while in this economy production, infection, and abatement parameters are heterogeneous across firms, q_w does not depend on these parameters. As a consequence, the design of any mechanism relying on markets for infection rights or Pigouvian taxes does not require information on the technological parameters of each individual firm, but just the knowledge of their distribution in the economy to calculate the efficient amount of infection rights to supply or their sale prices/taxes to levy. Importantly, however, even though the price of infection rights - or the Pigouvian tax rate - is the same for all firms, the total cost of infection rights borne by any firm will depend on its own production, infection, and abatement parameters. In particular, a firm of type f', characterized by a relatively lower productivity $A_{f'}$ or a higher marginal cost of abatement $\partial C_{f'}(a, L)/\partial a$, is likely to choose a lower level of abatement[17] and to have so a higher probability of infection $I_{f'}$. Firms of such types need then to buy a larger amount of rights (per worker employed); or equivalently the Pigouvian tax revenue levied on the production activity of these firms is higher.

Our findings then show that firms and/or sectors whose productivity loss associated to remote work is relatively small, that is, whose abatement costs are low, face a lower expenditure for the purchase of infection rights (or the payment of Pigouvian taxes) at equilibrium. On the other hand, firms and/or sectors for which abatement is more costly at the margin, will have a higher expense for infection rights (or Pigouvian taxes).[18]

[16]In the Online Appendix we show that the same result holds in an economy with production chains.

[17]The size of the employment $L_{f'}$ in a firm of this type will be smaller and this in turn affects the level of the marginal cost of abatement. The overall effect on the (efficient) equilibrium choice of abatement requires to take this effect also into account.

[18]In contrast, the effect of a more infectious technology (a higher value of $\gamma_{f'}$) on the total tax paid by a firm is ambiguous: firms operating such technology choose a higher level of abatement

Consider now extending the analysis to allow for heterogeneity in agents' preferences and infectiveness in consumption-leisure activities. In particular, suppose each individual $h = 1, 2, \ldots, H$ is characterized by distinct preferences $\beta_h, u_h(c, l)$, different infectiveness $\delta_h(l, \bar{l})$, and different health care costs, η_h. With heterogeneous agents distributional issues arise as efficient allocations are a whole frontier, not a single point. These issues can only partly be addressed allowing for lump-sum taxes/subsidies T_h indexed by h, as the heterogeneity of the disutility β_h of getting infected also affects the magnitude of the externality which needs to be internalized. In the case of utilitarian welfare, where all agents are equally weighted, the expression for the price of infection rights, once we suitably extend the definition of the competitive equilibrium with infection rights, becomes:[19]

$$q_l^h = A + \eta_h + \sum_{j=1}^{H} (A + \eta_j) \frac{\frac{1}{H}\frac{\partial \delta_j}{\partial \bar{l}}}{\frac{\partial \delta_h}{\partial l_h}} + \sum_{j=1}^{H} \frac{\beta_j}{\frac{\partial u_h}{\partial c_h}} \frac{\frac{1}{H}\frac{\partial \delta_j}{\partial \bar{l}}}{\frac{\partial \delta_h}{\partial l_h}}, \; h = 1, .., H \tag{4}$$

In (4) we see that, relative to the previous expression, (2), (i) the multiplicative effect of individual choices on other agents' infections (generated by social interaction activities) now varies across individuals[20]: $\Delta_h = \left[\frac{\sum_{j=1}^{H} \frac{1}{H} \partial \delta_j / \partial \bar{l}}{\partial \delta_h / \partial l_h} \right]$, (ii) this effect is weighted with the heterogenous utility and health costs across individuals. Furthermore, the term on the right hand side of (4) varies with the agent's type h so that, differently from the case of technological heterogeneity, one single market for infection rights does not suffice to implement an efficient allocation and personalized (type-indexed) prices q_l^h (or equivalently, personalized Pigouvian tax rates on agents' social interaction activities) are required.

These prices/tax rates are higher for agents whose marginal health care costs η_h are relatively higher and who are relatively more infective, in the sense that they have a larger multiplicative effect Δ_h (that is, for whom the effect of the agent's social interaction activity on the agent's own infection is smaller). Prices/tax rates are also higher for agents with relatively lower marginal utility for consumption $\partial u_h / \partial c_h$, as for instance richer agents: a higher price is needed to induce them to internalize their externalities. On the other hand, the individual own cost of getting infected, β_h, does not affect the agent's price of infection rights q_l^h (or the Pigouvian tax rates), as the effect of the agent's social interaction activities on the utility loss due to infection is already internalized in the agent's choice.[21]

but the overall effect on infections in the workplace could go either way.

[19] See the Online Appendix for details.

[20] Both in the expression of Δ_h and in (4), the derivatives of the functions $\delta_h(\cdot)$ are evaluated at $(l_h, \sum_j \frac{1}{H} l_j)$.

[21] The weighted average of the utility cost of getting infected for all individuals still appears in (4) because it contributes to determine the externality effect of the social interaction activities of an agent on other agents' infections.

Nonetheless, and similarly to the case of technological heterogeneity, the total payment/tax required from agents depends not only on the price but also on the amount of rights purchased, that is on the own infection probability I_l^h. This amount will be higher for agents with lower β_h and $\partial u_h / \partial c_h$, because such agents, other things equal, will choose a higher value of l and hence have a higher infection probability in equilibrium.[22]

Personalized prices of infection rights (or Pigouvian tax rates) with heterogenous consumers clearly impose stronger informational requirements to design markets for infection rights, easily satisfied if, e.g., the heterogeneity depends primarily on agents' demographic characteristics, generally observable (as in the case of taxation with tagging). In that case the analysis above implies that, for instance, younger agents, with lower health care costs of infection η_h, should face lower prices/tax rates q_l^h. At the same time, younger agents will also tend to exhibit a higher multiplier effect Δ_h (because of a smaller effect of their social interaction choices on their probability of getting infected) and this calls for a higher tax rate q_l^h.

Similar results obtain if we extend the analysis to allow the magnitude of the external effect of the social interaction activities of an individual on the infection of other agents to vary across individuals. This can be captured by replacing the average level $\bar{l}$ in the expression of $\delta_h(l_h, \bar{l})$ with a weighted average of the level of the social interaction activities of all individuals, with weights v_h reflecting the intensity of interaction with other agents. For instance, a high weight v_h may reflect the centrality of individual h in the network of social interactions, or the agent's strong preference for participating in large events like concerts or sport gatherings. The higher v_h, the higher the multiplicative effect Δ_h and the higher the price of rights (or the Pigouvian tax rate) faced by individual h.

We summarize our findings in the following:

Proposition (Prices of infection rights/Pigouvian taxes - with heterogeneity)**.** *Firms operating technologies with lower productivities or higher (marginal) costs of abatement will face the same infection rights' prices/Pigouvian tax rates as other firms (though the total tax paid by these firms will be higher). On the other hand individuals featuring higher health treatment costs, who are richer and who make social interaction choices with higher social dimension, will face higher infection rights' prices/Pigouvian tax rates.*

[22] The effect of the marginal probability of getting infected because of the own social interaction choices, $\frac{\partial \delta_h}{\partial l_h}$, on the other hand, is ambiguous, for reasons analogous to what we saw for γ_f in the case of the firms. The lower is $\frac{\partial \delta_h}{\partial l_h}$, other things equal, the higher is l_h, so the effect on I_l^h is ambiguous, while q_l^h, as we saw, is also higher.

4.2 Moral hazard

In the market design considered in the previous sections each firm and each agent must acquire rights for the infections it generates. As a consequence, the observability of the individual values of I_w and I_l, that is of the probability that an agent is infected at work and via his/her social interaction choices, is required to implement and enforce the competitive equilibrium with infection rights. In this section we show that the decentralization of the efficient allocation via markets for infection rights does not require this fine degree of observability at the individual level, only the observation of the average infection rate suffices.

Consider a society where only the health status of individuals is observable, but not where infections took place. Provided the number of individuals working in a firm is sufficiently large, we can say this captures the average value of the total probability of infection I of these individuals. Such limited observation generates a problem of *moral hazard* in teams, as in Holmstrom (1982), since both the choice of a by the firm employing the agents and that of the level l of social interaction by each of these agents contribute to determine the (average) probability that they are infected.

We show in what follows that in this environment it is still possible to decentralize the efficient allocation with markets for infection rights, provided we allow for lump sum taxes and subsidies not only for consumers but also for firms. Let I denote the average infection rate of agents working in a firm.[23] The institutional market design introduced in Section 3 is then modified as follows.

Each agent engaging in social interaction activities is mandated to buy - at the price q_l - a right per unit of probability of infection I;

Each firm employing L workers is mandated to buy a right per infected worker, IL in total, at the unit price q_w.

Not only the agent but also the firm pays a lump sum tax (receives a transfer if negative), given respectively by T and T^p.

Both the individual and the firm take into account how the value of I is affected, though only partly, by their own choices:

$$I = \gamma(1-a) + \sum_{h}^{L} \frac{\delta(l_h, \bar{l})}{L}.$$

[23] The argument and result can also be extended to the case where only the average probability of infection of an individual in the whole society is observed (that is, can be inferred from the available data).

Competitive equilibrium with infection rights and moral hazard. *A competitive equilibrium with infection rights and moral hazard is a competitive equilibrium with infection rights as previously defined, but i) the cost of infection rights for individuals and firms is given, respectively, by $q_l I$ and $q_w IL$; ii) the government chooses the same supply of infection rights Q* to consumers and firms*; iii) the market clearing condition for infection rights is simply $Q = IH$.*

At the competitive equilibrium with infection rights and moral hazard, total infections IH are equal to the level of the supply of rights Q set by the government. It is now straightforward to prove (in the Appendix) that, when Q is set equal to the efficient level of infections, the efficient allocation is decentralized also in the presence of moral hazard:

Proposition (Efficiency of equilibria with moral hazard)**.** *Suppose the government chooses a supply of infection rights Q equal to the efficient level of infections in the society, IH. Then the competitive equilibrium with infection rights and moral hazard induces the efficient allocation.*

The price of infection rights for firms q_w supporting the efficient allocation is the same with and without moral hazard, given by (1). The only difference is that now a lump sum transfer to firms is required. This is due to the fact that each firm needs to acquire a greater amount of infection rights, IL rather than $I_w L$ and so ends up paying also for the infections caused by its workers' decisions ($\sum_{j=1}^{L} \delta(l_j, \bar{l})$). This additional payment constitutes a lump sum tax paid by the firm via its purchase of infection rights, which must be offset with a lump sum rebate for the same amount to keep the level of its profits unchanged.

In contrast, the price of infection rights faced by agents q_l in the presence of moral hazard is L times the one obtained before, (2). This is due to the fact that with moral hazard each worker must acquire an amount of rights equal to the average infection rate among workers in the firm $\sum_{j=1}^{L} \frac{\delta(l_j, \bar{l})}{L}$, rather than to his/her individual infection rate $\delta(l_h, \bar{l})$. The agent's utility is only directly affected by the latter, but the agent ends up paying only a fraction $1/L$ of the infections generated by his/her chosen level of interaction. To preserve his/her incentives, the price of infection rights is then multiplied by L. Furthermore, the additional amount of rights the agent must purchase is determined by the social interaction choices of other individuals working in the firm, $\sum_{j \neq h}^{L} \frac{\delta(l_j, \bar{l})}{L}$, as well as on the abatement decisions by the firm, I_w. The payment for these other amounts is then independent of the agent's own decisions, thus a constant for him/her, analogous to a lump sum tax, which must be rebated back to the individual by suitably increasing the value of

$-T$ above the level obtained in Proposition (Efficiency of equilibrium), in the case without moral hazard.

To sum up, in the situation considered moral hazard can be fully overcome and the incentives of firms and agents sustained simply by increasing the amount of infection rights they are required to purchase and possibly by suitably increasing the price of rights. Budget balance is then preserved with suitable lump sum rebates.

Finally, the efficiency of equilibria with moral hazard extends to an economy which accounts for technological heterogeneity and multiple production as well as social interaction activity sectors. That is, competitive equilibria with infection rights are efficient even if it is not observable whether agents are infected in a production or social interaction activity nor, a fortiori, in which kind of production or activity sector.

4.3 Private information

We examine in what follows how the design of the markets for infections rights we considered (with fixed supply of rights), the variant of the design with fixed prices of these rights (or Pigouvian taxes) and the command economy fare in the presence of *private information* regarding the firm's productivity and/or the parameters capturing the infectiousness of production and social interaction activities. More precisely we consider situations where these parameters are subject to *unanticipated* shocks, whose realization is known to the agents or firms but not to the policy maker. The specification of the policy for the different interventions considered is set at the level which allows to attain the efficient allocation prior to the realization of the shock.

In the case of the command economy intervention, the values of a, l - and hence the allocation - are determined and cannot respond in any way to the realization of the shock. We have so a welfare loss. With a market for infection rights, when the policy maker fixes the quantity supplied (resp. the price) of these rights, this remains unchanged when the shock occurs but consumers' and firms' demand may vary and so prices (resp. quantities) adjust to clear. Hence the allocation obtained in equilibrium may still indirectly respond to the shock. Following the approach pioneered by Weitzman (1974)[24], we will evaluate and compare the welfare losses at the allocations obtained with the three distinct designs of policy interventions, relative to the efficient allocation after the shock realization. We will do so for different kinds of shocks, determining so in each case which intervention is preferable in terms of social welfare.

We evaluate first these effects for the firms' abatement level. Our findings[25] are summarized in the following:

[24] An interesting survey of a subsequent literature on the applications of the ideas in Weitzman (1974) to environmental control is Karp and Traeger (2018).

[25] See the Online Appendix for details.

Proposition (Welfare losses - abatement choice)**.** *The price setting design of infection rights induces, in the face of* private information *over the shocks to any of the parameters affecting the generation of infections γ, and the output and utility costs of infections $\eta, A, C(), \beta$, an abatement choice which is preferable in terms of social welfare, at least weakly, to both the command economy and the quantity setting designs.*

Figure 1a illustrates the result for the case of shocks increasing labor productivity A. In the command economy and the quantity setting design the value of a remains unchanged after the shock. Hence there is a positive welfare loss. With the price setting (or Pigouvian tax) design, the equilibrium value of a changes to the level that is efficient after the shock realization, so there is no welfare loss.

Turning then to the agents' social interaction choices, we have:

Proposition (Welfare losses - consumption-leisure choice)**.** *In the face of* privately observed *shocks to the infection process $\delta()$ the quantity setting of infection rights' design induces lower welfare losses associated to the agents' social interaction choice, for most parameter values, to both the command economy and the price setting designs. In contrast, in the face of shocks to the utility costs of infections β, price setting is preferable.*

Figure 1b describes the effects in the case of a shock decreasing the magnitude of the externality in infections in social interaction activities $\partial\delta/\partial\bar{l}$. In the command economy and price setting design the agents' social interaction choice remains unchanged, generating the welfare loss represented by the green shaded area. With the quantity setting design l instead varies, though less than at the optimum; the welfare loss is the (smaller) grid-patterned area.

Our findings thus show that the design of a market for infection rights allows to reduce, at least weakly, the welfare losses that we have with a command economy intervention due to shocks to parameter values of the economy that are only privately observed by individuals and firms. Furthermore, while the price setting design proves superior in the case of firms' abatement choices, this is not the case for agents' social interaction choices.

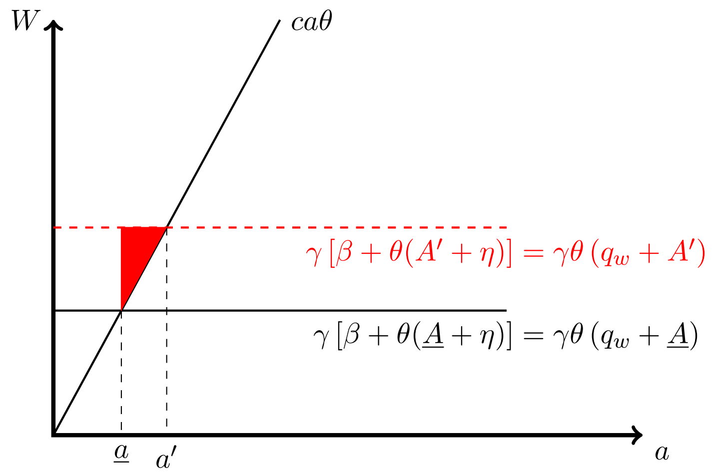
5 Conclusions

In this paper we study the role of markets for infection rights or, equivalently, Pigouvian taxes in an epidemic. In these conclusions we mention and briefly discuss several possible extensions of interest.

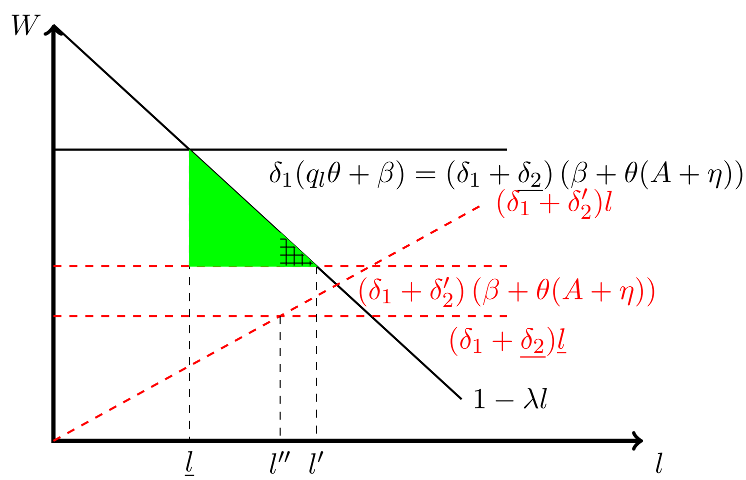
First of all, it is of interest to explicitly account for the dynamics of the epidemic, e.g., by integrating an epidemiological model into the analysis. In a dynamic environment the abatement decisions by firms and consumption-leisure choices of consumers affect not only current but also future infections, as the current process of infections also depends on the stock of susceptible individuals. In other words, infections have a negative externality in the present (as they produce more infections) and a positive externality in the future (as they contribute to herd immunity); see Garibaldi et al. (2020). While we do not explicitly model this trade-off, the main features of our analysis can easily be extended to account for it, with the prices of infection rights, or Pigouvian taxes, set so as to also internalize the dynamic externality.

Secondly, while we concentrate on the informational requirements of the mechanisms which allow to achieve efficient allocations, an interesting related question regards their institutional requirements. The institutional ability of a government to effectively enforce different policies is another important dimension along which to rank these mechanisms. In particular, Pigouvian taxes and markets for infection rights require levels of fiscal capacity and protection of property rights which might be hard to support in weak institutional environments. On the other hand, command interventions might also be hard to enforce in these contexts, especially when they require selective measures, like limiting production and consumption-leisure activities in some sectors rather than others and differentiating these limitations e.g., by technologies adopted and/or demographic groups. This suggests the relative informational requirements of these interventions, as we characterize them, are possibly a good proxy for how difficult it is to enforce them in terms of the required strength of institutions. Our analysis of the effects of private information, with "unanticipated shocks [to parameters] whose realization is known to the agents or firms but not to the policy makers," can also be used to gain insights in environments where policy makers are simply unable to enforce policy interventions that are conditional on the value of these parameters, even when they could observe them. More generally, weak institutional environments might be unable to enforce efficient allocations in a pandemic and are then led to rely more heavily on non-selective interventions, like general lockdowns. The latter require an effective police system. Hence this will be especially the case when a weak institutional environment is associated to the presence of limitations of social and civil capital which in turn suggest the presence of lower political economy costs of imposing restrictions on the individual freedom of citizens.

Figure 1: **Welfare losses with private information**



(a) Firms' abatement choice, increase in firm's productivity



(b) Agents' leisure choice, decrease in externality in social interaction

Parameterization: $u(c,l)=\theta c+l-\frac{1}{2}\lambda l^2$, $C(a,1)=\frac{1}{2}ca^2$, $H=F=1$, and $\delta(l,\bar{l})=\delta_1 l+\delta_2\bar{l}$. In Panel (a), $\underline{A}$ is the initial value of firm's productivity and $\underline{a}$ the associated efficient level of abatement; $A'>\underline{A}$ the value of productivity after the shock and a' the new efficient level of abatement as well as the new equilibrium with price setting. The color shaded area represents welfare losses for command economy and quantity setting designs. In Panel (b) $\underline{\delta_2}$ is the initial value of the externality in social interaction and $\underline{l}$ the associated efficient level of consumption-leisure; $\delta_2'<\underline{\delta_2}$ the value of the externality after the shock and l' the new efficient level of consumption-leisure and equilibrium with price setting. The color shaded areas represents welfare losses for command economy and price setting; the dashed area represents the smaller welfare loss with quantity setting when the equilibrium level changes to l''.

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Appendix: Proofs

Proof of Proposition [Efficiency of equilibrium - prices]. The first order conditions of the social welfare maximization problem are:

$$[\frac{\partial u}{\partial c}(A+\eta)+\beta]\gamma = \frac{\partial u}{\partial c}\cdot\frac{\partial C(a,L)}{\partial a}\frac{1}{L} \tag{5}$$

$$(\frac{\partial u}{\partial c}(\eta+A)+\beta)\delta'(l,l) = \frac{\partial u}{\partial l} \tag{6}$$

where - with some abuse of notation - $\delta'(l,l) \equiv \frac{\partial\delta(l,l)}{\partial l} + \frac{\partial\delta(l,l)}{\partial\bar{l}}$, that is, denotes the total derivative of $\delta(l,\bar{l})$ w.r.t. l and $\bar{l}$, evaluated at $\bar{l}=l$. The first order condition for the firm's optimal abatement choice at the competitive equilibrium with infection rights is instead

$$(A+q_w)\gamma L = \frac{\partial C(a,L)}{\partial a}. \tag{7}$$

It is immediate to verify that conditions (5) and (7) generate the same choice and allocation if q_w is set as in (1).

Consider then the first order condition with respect to l for the agent's maximization problem in the competitive equilibrium,

$$\frac{\partial u}{\partial l} = (\beta+\frac{\partial u}{\partial c}q_l)\frac{\partial\delta(l,\bar{l})}{\partial l}. \tag{8}$$

Conditions (6) and (8) support the same choice if $\left[\frac{\partial u}{\partial c}(\eta+A)+\beta\right]\delta'(l,l) = (\beta+\frac{\partial u}{\partial c}q_l)\frac{\partial\delta(l,\bar{l})}{\partial l}$; that is, if $q_l = (\eta+A)\frac{\delta'(l,l)}{\partial\delta(l,\bar{l})/\partial l} + \frac{\beta}{\partial u/\partial c}\left(\frac{\delta'(l,l)}{\partial\delta(l,\bar{l})/\partial l}-1\right)$, which can be rewritten as (2).

Finally, substituting the expressions obtained for the prices of infection rights into the government budget constraint, after some algebra, we get the expression of the lump sum tax T in (3). It is easy to see that both terms on the right hand side of (3) are negative, since both q_w and q_l are strictly greater than η, hence T has a negative sign. □

Proof of Proposition [Efficiency of equilibria with moral hazard]. The argument develops along the same lines as the proof of Proposition (Efficiency of equilibrium). Consider the first order condition for the firm's choice of abatement at a competitive equilibrium in the current environment. Substituting the market clearing conditions for infection rights, labor and the consumption good yields:

$$(A+q_w)\gamma L = \frac{\partial C(a,L)}{\partial a}, \tag{9}$$

the same expression as the one obtained with no moral hazard, (7). Hence the value of q_w inducing the optimal choice of a is unchanged. However each firm needs to acquire a greater amount of infection rights, IL rather than $I_w L$. To keep its net payments the same a lump sum rebate is thus needed.

The first order condition for the worker's optimal choice of leisure at a competitive equilibrium, after substituting the market clearing conditions, is instead:

$$\left(\beta + \frac{\partial u}{\partial c} q_l \frac{1}{L}\right) \frac{\partial \delta}{\partial l} = \frac{\partial u}{\partial l}, \tag{10}$$

It differs from the one obtained in (8) for the fact that q_l is now multiplied by $1/L$. To be able to still match the first order conditions for a Pareto optimum, q_l must then be L times its value in the absence of moral hazard. This feature, together with the fact that in equilibrium each agent must also acquire a greater amount of infection rights, equal to $I_l + I_w$ instead of I_l, requires a higher value of the lump sum rebate received by agents, to offset the extra payment made by them. □