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Lockdown Policy Choices, Outcomes and the Value of Preparation Time

A stylised model

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Abstract

In the anticipation of a widely accessible vaccine or an effective cure for the Coronavirus disease (COVID-19), governments have resorted to non-pharmaceutical measures, notably lockdowns, to limit the number of infections, without overwhelming their health systems. In the short-run, this new objective of "flattening the epidemic curve" may however be at odds with incumbent ones, such as promoting economic growth. To the extent that the epidemic generates a conflict between these objectives, societies and their decision-makers have to arbitrate between them. Using a stylised static model, this paper proposes a policy rule that determines a country's optimal lockdown intensity as a function of social preferences, the strength of the epidemic and the characteristics of the economy, namely sectoral structure, health care capacity, fiscal space and lockdown compliance. The optimal lockdown determines a set of 'outcomes' in terms of welfare, production, income (which is considered to be related to the post-epidemic economic potential) and untreated infections. The model further takes into account that the sequential outbreak of the epidemic has conferred preparation time to some countries, which has raised the mitigation efficiency of lockdowns. Ceteris paribus, the social welfare loss declines the later an outbreak occurs, implying that the first countries affected act as shock absorbers, providing countries hit at a later stage with a 'windfall benefit'. Collectively, a sequential outbreak is thus less costly than a symmetric one. Separately, the paper also shows how optimal lockdown policies change when there is uncertainty about the strength of the epidemic and mitigation efficiency, respectively, and how targeted measures (e.g. closure of contact-intensive sectors or the protection of vulnerable groups) alter the nature of the income-infections trade-off with respect to general lockdowns.

JEL Classification: D8, E6, I15, I18.

Keywords: coronavirus disease, COVID-19, lockdown, epidemic, public health, macroeconomic stabilisation, policy objectives, uncertainty.

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CONTENTS

1. INTRODUCTION AND MOTIVATION

A sudden and rapid spread of a severe disease poses a major challenge for public health authorities and governments more generally. As health systems become overwhelmed, authorities' leading prospect to save lives is to try managing and containing the epidemic. This new objective of tackling the public health emergency by "flattening the epidemic curve" may however be detrimental to incumbent ones, such as promoting economic growth. To the extent that the epidemic generates a conflict between these objectives, societies and their decision-makers have to arbitrate between them. The outbreak of the novel Coronavirus disease (COVID-19),[1] which first emerged in China at the end of 2019 and has so far (23 June 2021) caused 3.8 million deaths worldwide, including about 730 000 in the EU, fits into this pattern. In anticipation of a widely accessible vaccine[2] or an effective cure, governments have resorted to non-pharmaceutical measures, and notably lockdowns, to slow down the transmission of the disease. The combined effect of the pandemic and lockdowns resulted in an unprecedented economic collapse across the world, with global and EU Gross Domestic Product (GDP) plunging by 3.3% and 6.2%, respectively, in 2020.

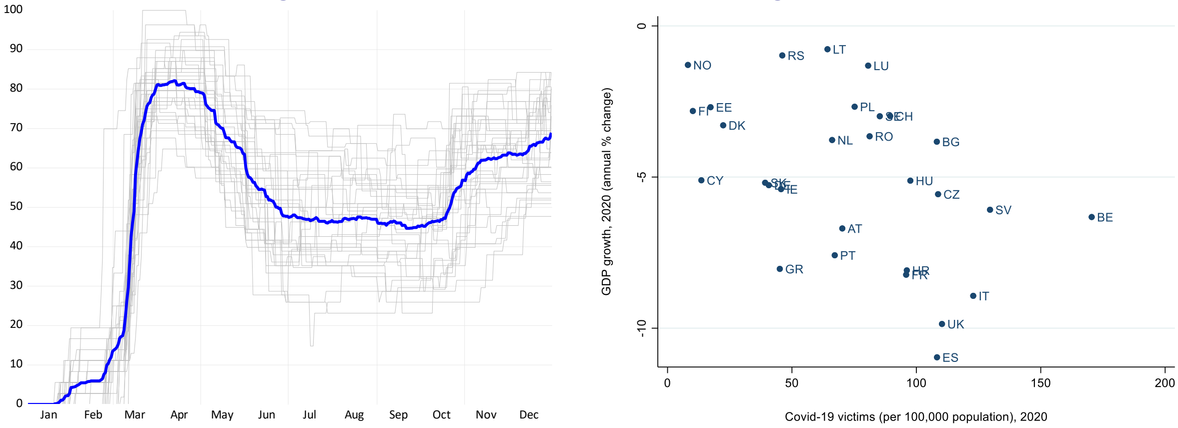
While short-run arbitration between public health and output objectives is thus required from any society facing an epidemic, the decision-making context generally differs in line with each society's characteristics. In Europe (like elsewhere), significant cross-country variation[3] can be observed both in the way COVID-19 was tackled and in terms of its 'outcomes', namely the number of infections or victims on the one hand, and the severity of the output losses on the other. While the broad lockdown patterns have been comparable throughout 2020, there has been significant dispersion in the lockdown intensity (Chart 1, left panel). As illustrated in Chart 1 (right panel), the pandemic has caused a high number of victims and a strong contraction in GDP in all countries, with some countries seemingly worse hit in both dimensions. This suggests that the nature of the trade-off between infections and output that an epidemic generates for an individual country is likely to differ across countries. Indeed, the country-specific trade-off and the epidemic's overall impact are likely to be determined by domestic characteristics and conditions, other than a relative preference for one of the two outcomes.

This paper proposes an intuitive framework explaining the observed country variation in outcomes. It derives a policy rule that determines a country's lockdown intensity as a function of policy-preferences, the strength of the epidemic and the characteristics of the economy, i.e. its sectoral structure, fiscal space, health care capacity and societal behaviour. The proposed model further considers that with a sequential epidemic outbreak, the news about the first outbreak (which is an unexpected event) provides valuable preparation time to other countries, raising the mitigation efficiency of the latter's lockdown (the epidemic as an anticipated event). This preparation time can be used to prepare health systems for a surge in patients or to organise the lockdowns, including compensatory measures. Meanwhile uncertainty about the strength of the epidemic and the ability to mitigate it, respectively, alter the optimal lockdown intensity with respect to a deterministic set-up. This is particularly relevant in the case of COVID-19, owing to its novel character. The optimal

[1] The World Health Organisation characterised COVID-19 as a public health emergency of international concern on 30 January 2020 and as a pandemic on 11 March 2020. This paper generally refers to an epidemic in relation to the theoretical model, while the term pandemic is used specifically for COVID-19.
[2] In the European Union, the first vaccine to prevent COVID-19 was approved at the end of December 2020 by the European Commission, following an evaluation by the European Medicines Agency (EMA).
[3] Given that the COVID-19 pandemic is still ongoing, conclusive statements are premature. The data used in this paper refer to 2020.

lockdown determines a set of 'outcomes' in terms of social loss, the number of untreated infections, production and income.

Chart 1: **Lockdown stringency and COVID-19 impact on lives and growth in Europe, 2020**

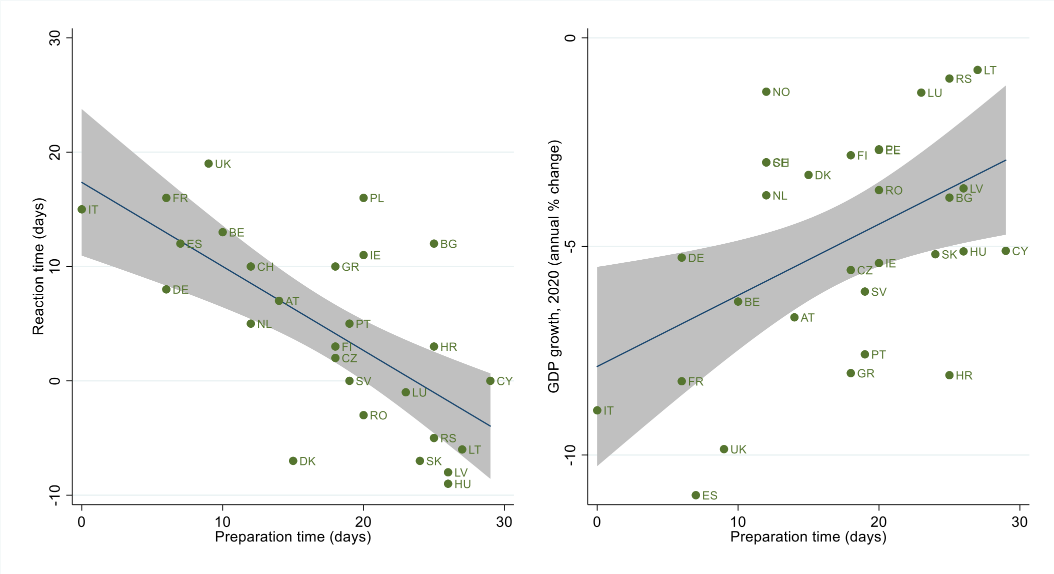


Note: the blue line in the left chart displays the average lockdown stringency for European countries. For Ireland, GDP is replaced by Modified Domestic Demand (right chart).

Source: own calculations based on Oxford COVID-19 Government Response Tracker database (Hale et al., 2020) and Eurostat.

The value of preparation time is a central element of this paper. Evidence from Europe suggests that countries that were hit earlier by the epidemic took longer to react and implement countrywide stay-at-home requirements than countries affected later (see Chart 2, left panel). For example, Italy, which was the first country in Europe affected by the outbreak, took longest to impose a countrywide stay-at-home-requirement: it took 11 days from the day on which more than 15 victims were recorded (28 February 2020) to the imposition of these requirements (10 March 2020). Other European countries, which experienced later outbreaks, had often already imposed similar requirements before reaching the same infection thresholds. Denmark, for example, imposed stay-at-home requirements on 3 March 2020, i.e. 21 days before recording 15 COVID-19 fatalities and a week earlier than Italy (note that some local lockdowns were already in place in Italy towards the end of February). This suggests that many countries reacted to outbreaks observed abroad (i.e. in Italy and the first countries affected) rather than at home. A longer preparation time for an imminent outbreak indeed appears to be associated with a milder contraction in GDP in the first half of 2020 (Chart 2, right panel and annex) and less victims of the pandemic, suggesting that the sequence of outbreaks matters in determining outcomes. The first country affected effectively acts as an involuntary shock absorber ("canary in the coalmine") for others, with preparation time provided being akin to a windfall endowment.

Chart 2: **Preparation time (days) versus reaction time (days) and GDP change**



Note: Preparation time refers to the number of days between the outbreak of the disease (100 confirmed cases) in Italy and in a given country. Reaction time measures the number of days between the outbreak of the epidemic in a country and the imposition of stay at home requirements (negative values imply that countries had measures in place ahead of the outbreak).

Source: own calculations based on Oxford COVID-19 Government Response Tracker database (Hale et al., 2020) and Eurostat

This paper contributes to the literature on the economic consequences of epidemics, which has been expanding fast following the emergence of the Coronavirus and the lockdowns imposed worldwide. While earlier papers focus on estimating the macroeconomic costs of different pandemic scenarios (Jonung and Roeger, 2006; Keogh-Brown et al, 2010), more recent ones incorporate the interactions between economic outcomes and the severity of the epidemic (e.g. Eichenbaum, Rebelo and Trabandt (2020), who integrate the so-called susceptible-infected-recovered (SIR) model of epidemiology into a dynamic macroeconomic model). These frameworks suggest the existence of a general trade-off whereby infections increase with economic activity (consumption or hours worked). As many papers show, the nature of the trade-off may differ because of endowments, the efficiency of different types of targeted containment measures or the availability of testing and tracing capacity. Mendoza et al. (2020) and Ichino et al. (2020) notably show how a saturated health system reduces output. Meanwhile, Acemoglu et al. (2020), for example, suggest that lockdown policies that differentiate between risk or age groups, in combination with testing and isolation of infected persons (corroborated by Aum, Lee and Shin (2020)) lower both the economic and human loss with respect to optimal uniform policies. Related to containment efficiency considerations, Demirgüç-Kunt et al (2020) find that countries which rolled out non-pharmaceutical interventions early in the COVID-19 pandemic, suffered both lower economic loss and less deaths from the virus (which propagates exponentially), compared to countries that reacted less swiftly. Like the lockdowns, the policy reaction to cushion its adverse effects has been unprecedented in most jurisdictions. Pfeiffer, Roeger and in't Veld (2020) show that the economic policy measures (short-term work allowances and liquidity support for firms) deployed in reaction to the COVID-19 pandemic in the EU compensated for the output losses, albeit only partially. This is in line with the empirical assessment by Deb et al. (2020), who find that short-term economic losses were smaller in countries that extensively deployed their fiscal and monetary policies. Finally, and reflecting the 'novelty' of the Coronavirus and the associated unknowns (Anderson et al., 2020), this paper also relates to the literature on decision-making under uncertainty, in line with Brainard (1967). In particular, it shows how lockdown decisions are affected by different types of uncertainty.

The linear and static nature of the model proposed in this paper means that the epidemic is represented as a single event and that there is a clear (one-period) trade-off between infections and production. This entails some obvious limitations. In particular, it does not capture the state-dependency of the effect of marginal changes in the lockdown intensity on infections and production, respectively. Similarly, it does not allow comparing different intertemporal lockdown strategies during the pandemic, e.g. a stable lockdown level versus suppression versus "stop and go" policies, under which loose and tight lockdown phases alternate (Gros and Gros (2020).[4] However, it provides a tractable framework to understand and assess the observed country variation in lockdown policies and outcomes, which captures many of the factors affecting the nature of the trade-off, and which are also integrated in the papers referred to above.

The remainder of the paper is structured as follows: section 2 presents the baseline model, which is extended in section 3 by introducing endowments and mitigation efficiency. Section 4 considers how different forms of uncertainty affect decision-making and outcomes. Section 5 discusses the implications of a sequential outbreak and the value of preparation time. While the focus of the first sections is on general lockdown policies, section 6 extends the model to accommodate targeted measures, such as working from home or target confinements. The annex provides some empirical support to the model and examines how the variables included in the theoretical model - notably preparation time - contribute to explaining the variation in the GDP drop in 2020 and COVID-19 fatalities.

2. THE BASELINE MODEL: A SIMPLE FOUNDATION FOR A LOCKDOWN POLICY RULE

Virus outbreak and mitigation: The starting point of the model is the outbreak of a virus disease (epidemic). It is assumed that, in the absence of a vaccine, an unmitigated propagation would affect a share $\nu \leq 1$ of the population. It is further assumed that this *latent* infection number, which gauges the severity of the epidemic,[5] is determined by two variables capturing living and working conditions, respectively. The first one, φ, captures the number of infections as a share of the population, which would result from societal and population characteristics. These include behaviour (van Bavel et al., 2020), age structure (Ferguson et al., 2020), population and household density, meteorological conditions and air pollution (Lolli et al., 2020), pre-existing immunity (Doshi, 2020) or genetic risk factors (Zeberg and Pääbo, 2020). For the present purposes, it is not necessary to model this in greater detail. The second variable, $\alpha \geq 0$, corresponds to the share of sectors that have operational characteristics requiring personal interaction ('social' or 'contact-intensive' sectors). These characteristics entail a negative externality in the form of a faster and wider spread of the disease. Latent infections are thus determined as follows (population is normalised to 1):

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[4] Nonetheless, the model can be used for comparative statics, including comparisons of different periods within the same pandemic.

[5] The actual number of infections would be given by the area under the epidemic curve, which depends on the reproduction number (R_0) of the virus. Absent of any mitigation measure, this would correspond to the number of infections associated to 'herd immunity' achieved through infections rather than vaccination. For intuitive purposes (there is no direct functional correspondence), ν could be considered as the peak height of the epidemic curve.

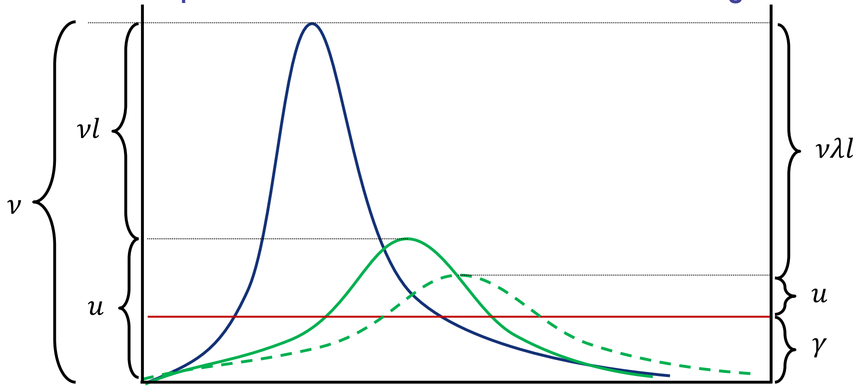
(2.1) $\nu = \varphi + \alpha$

In this deterministic setting, the latent infection number is assumed to be known with certainty (an assumption that is relaxed in section 4). It is further assumed that all infected persons require treatment.[6] Without a health care system that can provide treatment to infected individuals, the only possibility to limit the impact of the disease is by avoiding infections. This can be achieved by non-pharmaceutical interventions (NPIs), such as stay-at-home requirements that mitigate the transmission of the virus. While such measures eliminate contamination opportunities between infectious and susceptible individuals, they also provide a signal to alter behaviour (e.g. regular handwashing, wearing of masks, avoidance of crowds).[7] The intensity of NPIs can be expressed as the share of the population that is effectively 'locked down' following their application (i.e. it is akin to a reduction in the population). The general lockdown intensity, $l \in [0;1]$, is set by the policy-maker with full knowledge of its mitigating impact (this assumption is relaxed is section 4). The number of (untreated) infections after the application of mitigation measures, u, can be expressed as follows: [8]

(2.2) $u = \nu(1 - l)$

Equation 2.2 can be rewritten as $\nu = \nu l + u$, where the latent strength of the epidemic is decomposed into avoided (νl) and non-avoided, i.e. untreated (u), infections (Chart 3, left axis).

Chart 3: **Decomposition of maximum infection number and mitigation efficiency (illustrative analogy)**



Note: The left and right axes correspond to equations (2.2) and (3.1). The chart shows epidemiological curves without mitigating actions (blue), with lockdown (green), with efficient ($\lambda > 1$) lockdown (dotted green). The size of the health care system is represented by the red line.

Production: Let ω be the economy's labour force, expressed as a share of the population. Assuming that production exclusively depends on labour, the economy's output in the absence of a lockdown is given by:

[6] Applied to COVID-19, these can be thought of as symptomatic cases requiring hospitalisation.
[7] NPIs may take the form of direct stay-at-home requirements or measures with an equivalent effect, such as mobility restrictions (e.g. public transport limits), curfews or school closures, which may require the presence of parents at home.
[8] As above, $\nu(1 - l) \geq 0$ would be analogous to the area under the flattened epidemic curve. Intuitively, it could be considered as the peak height of the epidemic curve. Indeed, mitigation would lower the peak of the epidemic, but also push it out into the future, resulting in a longer duration of the epidemic. While the duration of the epidemic is not considered, given the static nature of this model, a lockdown would nonetheless result in less infections (smaller area under the flattened curve).

(2.3) $\tilde{y} = \omega$

The imposition of NPIs during an epidemic however prevents individuals required to stay at home from engaging in their economic activity. As such, the lockdown intensity directly reduces the available labour force and scales down production (the economic structure is neutral in determining output[9]):

(2.4) $y = \omega(1 - l)$

Infections-production trade-off: Solving the mitigation equation (2.2) for l and substituting it into the production equation (2.4) yields the trade-off between production and untreated infections:

(2.5) $y = \frac{\omega}{\nu} u$

This "possibility frontier" connects all combinations of u and y that are feasible for the economy (Chart 4). The nature of the trade-off hence depends on the ratio ('relative price') between potential production and the latent magnitude of the epidemic: reducing the share of persons that are untreated by one, implies sacrificing ω/ν units of production. The trade-off is thus also determined by the economic structure, α, through its effect on latent infections (cf. equation 2.1).

The linear possibility frontier implies that there is no direct impact of infections on the level of output. In (u, y) space, the extreme choices of no lockdown ($l = 0$) or a full lockdown ($l = 1$), would respectively yield the bundles (ν, ω) and $(0,0)$. In other words, it would be possible to achieve full production at the cost of accepting the full impact of the epidemic, or to suppress fully the disease in return for entirely forfeiting production. Both of these extreme scenarios would unlikely be achievable in reality, notably because the disease would reduce the labour force on the one hand, and some essential functions of the economy would need to continue. Nonetheless, the linear approximation would seem reasonable for two reasons: first, severe COVID-19 (including fatalities) disproportionally affects persons outside of the working-age population. Second, as will be shown below, these extreme choices (i.e. no and total lockdown, respectively) would be ruled out under reasonable assumptions on preferences, and do not correspond to policies implemented in Europe.[10]

Social loss function and choice: To a policy-maker acting on behalf of society, tackling the epidemic adds a dimension to its decision-making space. The policy-maker will seek to minimise both u, and the production loss relative to the non-epidemic level, given by $\tilde{y} = \omega$.[11] The optimal lockdown policy implemented will be the one that minimises a social loss function of the form:

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[9] In this setting, the lockdown is indiscriminate and does not target contact-sensitive sectors or risk groups. Targeted lockdowns are discussed in section 6. While it is acknowledged that targeted lockdowns have (eventually) become part of many countries' response to the COVID-19 pandemic, many lockdown measures have been general (e.g. mobility restrictions; school closures that prevent parents from going to work, regardless of the sector they are employed in).

[10] While an extension of the model in this respect would be warranted, it goes beyond the scope of the simple framework presented in this paper.

[11] It is acknowledged that the literature provides conflicting evidence on the complementarity or substitutability of government-imposed lockdowns and voluntary social distancing measures. Here it is assumed that the government and social preferences are aligned, or that the preferences are those of a representative individual (median voter).

(2.6) $$L = \frac{\theta}{2}u^2 + \frac{(1-\theta)}{2}(\tilde{y} - y)^2$$

where $\theta \in [0; 1]$ is the loss parameter assigned to untreated infections.[12] The quadratic social loss function implies an increasing marginal loss, i.e. the penalty on deviations from the target levels accelerates with the deviation. The shape of iso-loss (indifference) curves, showing combinations of u and y that will yield a given social loss, depends on θ.[13] Substituting (2.2) and (2.4) into (2.6), taking the first order condition, i.e. setting $(\partial L/\partial l) = 0$, and solving for l, yields the optimal lockdown policy, which is found to be

(2.7) $$l^* = \frac{\theta \nu^2}{\theta \nu^2 + (1-\theta)\omega^2}$$

This lockdown policy rule has important implications. An increase in the latent strength of the epidemic, for example as a result of a more aggressive virus strain, will result in a more stringent lockdown ($\partial l^*/\partial \nu > 0$), in order to reduce the number of infections. Since the latent infection number is determined by the economic structure, it also follows that countries with a higher share of 'social sectors' will experience stricter lockdowns ($\partial l^*/\partial \alpha > 0$). Meanwhile, the lockdown intensity declines in the size of the labour force ($\partial l^*/\partial \omega < 0$), as the absolute economic loss would be higher. Finally, social preferences matter in determining the lockdown intensity ($\partial l^*/\partial \theta > 0$): the higher the importance attached to avoiding untreated infections, the stricter the lockdown (Chart 3).

Substituting the equilibrium lockdown into equations 2.2 and 2.4 yields the corresponding equilibrium outcomes:

(2.8) $$u^* = \frac{(1-\theta)\omega \nu}{\theta \nu^2 + (1-\theta)\omega^2}$$

(2.9) $$y^* = \frac{(1-\theta)\omega^2}{\theta \nu^2 + (1-\theta)\omega^2}$$

Potential production, the latent strength of epidemic and preferences hence jointly determine the output level and the number of untreated infections. The response of the equilibrium number of untreated infections to a change in the latent strength of the epidemic would depend on the initial state. It can be shown that the equilibrium number of untreated infections would be highest at $\nu^\theta = \omega\sqrt{(1-\theta)/\theta}$,[14] and thus be greater for societies attaching more importance to output. In other words,

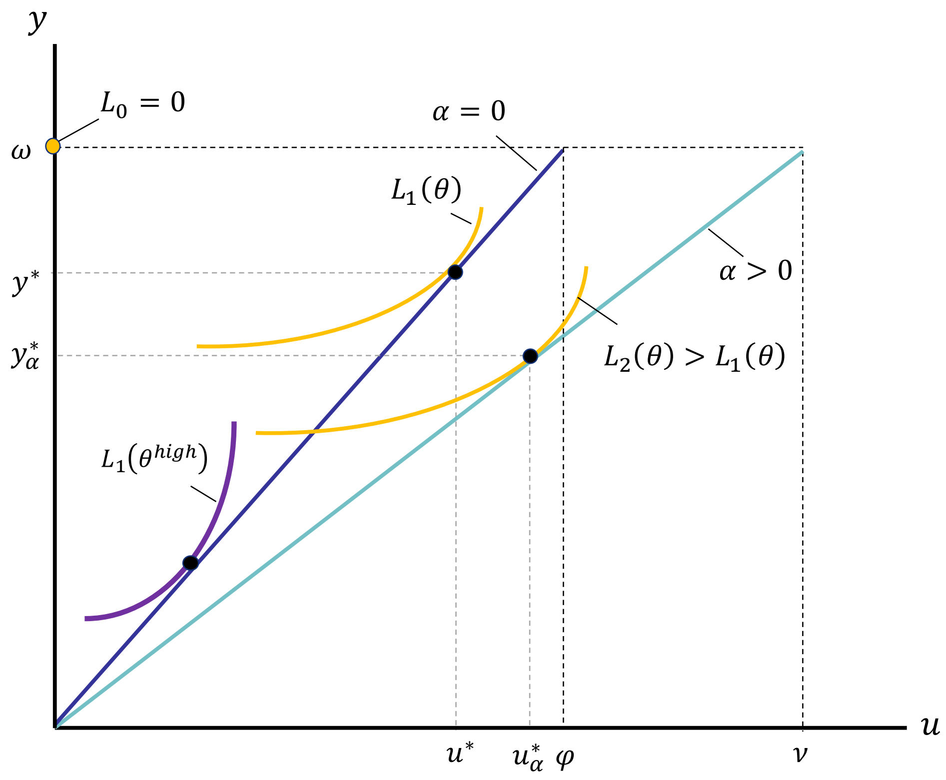
[12] Note that the first argument could be written as $(u - \tilde{u})^2$, with $\tilde{u} = 0$. While it can reasonably be assumed that the government's objective is to avoid untreated infections, it is however imaginable that $\tilde{u} > 0$ for the purpose of developing and testing a vaccine. This case is not considered here.

[13] In (u, y) space, they would give rise to concentric circles around $(0, \tilde{y})$ for $\theta = 1/2$. $\theta < 1/2$ (higher preference for preserving income) and $\theta > 1/2$ (higher preference for minimising infections) would give rise to wide and high ellipses, respectively.

[14] By setting $\partial u^*/\partial \nu = 0$. The impact will depend on whether the substitution effect (change in ω/ν) outweighs the income effect.

if the initial strength of the epidemic were given by ν^{θ}, u^{*} would decline regardless of the direction of change in ν.

Chart 4: **Production-infection trade-off (possibility set) and social loss function**



Note: The chart illustrates the possibility frontier (2.5) and the associated optimal lockdown (2.7) for $\alpha = 0$ and $\alpha > 0$. Different social preferences (θ) are represented by the yellow and purple indifference curves. At point (0, ω) social loss is zero regardless of preferences.

3. AUGMENTING THE LOCKDOWN POLICY RULE: ENDOWMENTS AND MITIGATION EFFICIENCY

This section augments the baseline model of section 2 by allowing for the existence of endowments, namely health care capacity and fiscal space, as well as lockdown compliance which determines mitigation efficiency.

Health care capacity and mitigation efficiency: It is now assumed first that a health care system exists that can treat a share γ of the population.[15] That health system would be saturated, i.e. leave some infected persons untreated, if net latent infections are positive, i.e. $\nu - \gamma > 0$.

Furthermore, the ability of societies and institutions to react to the collective threat that the epidemic represents, affects the efficiency of mitigation policies put in place. Mitigation efficiency, denoted by $\lambda \geq 0$, can amplify or attenuate the effect of a given lockdown intensity l on avoiding infections. The

[15] Here, treatment capacity is interpreted widely, capturing the number of hospital beds, intensive care units (ICUs), medical staff available and medication. It is assumed to be fixed, implying for example that there would be no reduction in medical staff due to infections.

infection mitigation equation (2.2) can then be rewritten as equation (3.1) below. λ is a function of the degree of compliance with the virus mitigation policy, denoted by δ (equation 3.2). The latter is an intrinsic country-specific characteristic and can be interpreted as the ease of changing societal behaviour in view of aligning it with the recommendation of public health authorities, either voluntarily or through enforcement. It thus captures different factors that impact behavioural choices, such as trust in institutions and science, quality of communication by the public health authorities, social norms[16] and the cultural context (van Bavel et al., 2020; Gelfand et al. 2021). It can also capture experience with virus outbreaks in the past (e.g. SARS) and general preparedness for emergencies or disasters. With both γ and δ set to zero, the infection mitigation equation would revert to its original form in the benchmark model above.

(3.1) $$u = \nu(1 - \lambda l) - \gamma,$$

(3.2) $$\lambda = (1 + \delta), \text{ where } \delta \geq -1$$

The first implication of equation (3.1) is that a country can now lower untreated infections in two ways: by avoiding them through the imposition of a lockdown, or by using its health care system and providing treatment to infected persons. The second one is that mitigation efficiency will determine the 'price' of flattening the epidemic curve (chart 2). With values of γ and λ, such that $(\nu - \gamma)/\lambda\nu < 1$, untreated infections could be fully avoided by a combination of mitigation and treatment, without needing to resort to a full lockdown. Conversely, with values such that $(\nu - \gamma)/\lambda\nu > 1$, even a complete lockdown and the full exhaustion of the health system's capacity would not suffice to avoid untreated infections.

Production and fiscal space: In this static setup, the lockdown represents a non-recoverable production loss. However, a government may have the resources to replace the foregone income by a transfer, g. There may be different justifications for such a transfer. In particular, the standstill of the economy caused by the lockdown can entail hysteresis effects causing permanent damage to the economic potential. Support to households and firms through transfers, can preclude defaults of illiquid firms, encourage labour hoarding by avoiding the severing of employer-employee relationships, and thereby preserve the productive capacity for the post-epidemic era. Moreover, the transfer provides subsistence support to those sectors of the economy disproportionately affected by the lockdown.

The transfer is bound by the available fiscal space $\bar{g}$, i.e. $g \leq \bar{g}$. Fiscal space is a country-specific endowment when entering the epidemic and essentially corresponds to the maximum amount the government is able and willing to mobilise during it.[17] Total disposable income is the sum of actual production (output) income, defined in (2.4), and the transfer:

(3.3) $$I = y + g$$

[16] For example, Gelfand et al. (2021) find that countries with "tight" cultures, i.e. strict norms and punishments for deviance, experienced less COVID-19 cases and fatalities relative to their population than countries with "loose" cultures, which have weaker norms and are more permissive. Gelfand et al. point out that the relative advantage of cultural tightness over looseness is context-specific. For example, while looseness, i.e. deviation from traditional rules, may indeed support the propagation of a virus, it may also spur creativity and innovation in another setting.

[17] While modelled for simplicity as an endowment rather than as an intertemporal budget, it can be thought of as a country's capacity to borrow at a sustainable interest rate, a rainy day/sovereign wealth fund or a cash buffer.

It can be further assumed that the transfer would be limited to the amount necessary to maintain income at the level of potential production, i.e. $I \leq \tilde{y}$. The higher y, the lesser the compensation that would be needed.

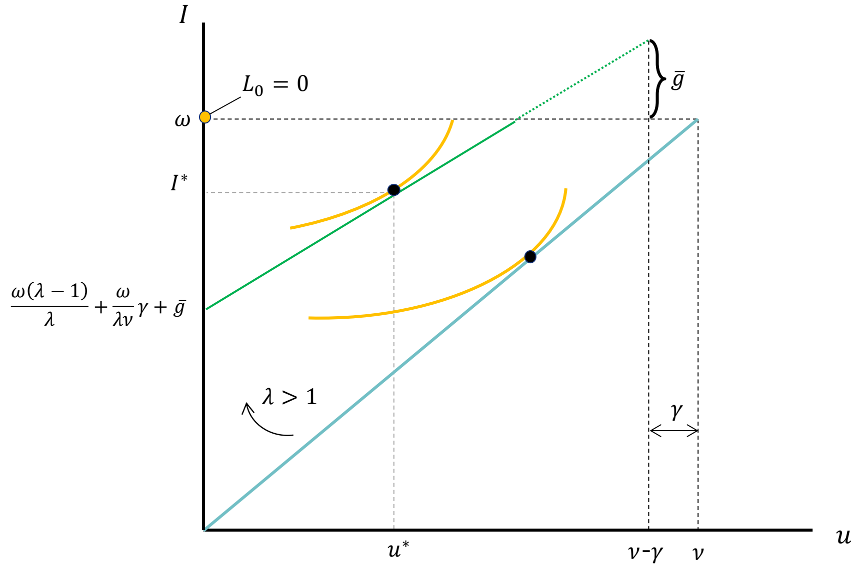
<u>Infections-income trade-off</u>: Solving the new mitigation equation (3.1) for l and substituting into the income equation (3.3), yields the new possibility frontier connecting all available combinations of u and I:

(3.4) $$I = \frac{\omega(\lambda - 1)}{\lambda} + \frac{\omega}{\lambda \nu}\gamma + g + \frac{\omega}{\lambda \nu}u$$

The nature of the trade-off changes depending on a country's endowments and mitigation efficiency. Compared to the possibility frontier in the previous section (2.5), the trade-off now has an intercept (given by the three first terms) and a different slope (coefficient on u). The implication of this is that the bounds on both the lockdown intensity and outcomes may change. An intercept higher than $\bar{g}$ implies that infections can be either avoided or treated in full, by setting $l^{UB} = (\nu - \gamma)/\lambda\nu$. The health system and positive lockdown compliance thus represent a safety net, determining the worst-case scenario for production. Conversely, an intercept smaller than $\bar{g}$ would indicate that an economy would necessarily suffer untreated infections even under a maximum lockdown, i.e. the full exhaustion of health care system would not suffice to compensate for the inefficient mitigation. By using its fiscal space, a government can maintain income at the level of potential production, ω, by setting $l^{LB} \leq \bar{g}/\omega$. Fiscal space hence introduces a lower bound on the lockdown intensity, which in turn lowers the worst-case number of untreated infections, $u(l^{LB}) = \nu(1 - \lambda\bar{g}/\omega) - \gamma$. Fiscal space essentially renders a lockdown affordable, as it offsets parts of the lost production revenue.

Changes in mitigation efficiency (λ) will alter the relative impact of the lockdown on u and y, respectively, and cause a rotation in the infections-production possibility frontier around point (ν, ω) (chart 5). A higher compliance with NPIs implies a clockwise rotation (more infections can be avoided for a given lockdown intensity) and vice versa.

Chart 5: **Income-mitigation trade-off (possibility set) with endowments and mitigation efficiency**



Note: The chart illustrates the possibility frontier (3.4) without (blue) and with endowments (green) and the associated optimal lockdown (3.6). Lockdown compliance is assumed to be positive ($\lambda > 1$), implying that the possibility frontier rotates clockwise.

The government sets the intensity of l by substituting (3.1) and (3.3) into its social loss function (3.5), where the focus is now on the deviation from desired disposable income ($\tilde{I} = \tilde{y}$) rather than potential production:

(3.5) $$L = \frac{\theta}{2}u^2 + \frac{(1-\theta)}{2}(\tilde{y} - I)^2$$

Minimising (3.5) yields the following lockdown policy rule:

(3.6) $$l^* = \left(\frac{\theta\lambda\nu}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2}\right)(\vartheta - \gamma) + \frac{(1-\theta)\omega}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2}\bar{g}$$

This lockdown policy rule offers interesting insights on the role of endowments. The lockdown intensity will increase with fiscal space ($\partial l^*/\partial\bar{g} > 0$), which renders the lockdown more affordable. Meanwhile, the lockdown intensity will decrease with the size of the health care capacity ($\partial l^*/\partial\gamma < 0$), which reduces the need to prevent infections. The effect of a change in mitigation efficiency on the lockdown intensity ($\partial l^*/\partial\lambda$) is ambiguous and state-dependent. The lockdown would be strictest at $\delta^l = \frac{\omega}{\vartheta}\frac{\sqrt{\theta(1-\theta)}}{\theta} - 1$. As δ moves away from δ^l, the lockdown intensity would necessarily loosen: by making it easier to "flatten the curve", higher compliance makes a strict lockdown less necessary, thereby allowing to stabilise production. In contrast, it would become too onerous to compensate for a reduction in compliance by foregoing an even higher share of production.[18]

[18] It can be shown that $\partial\delta^*/\partial\theta < 0$, i.e. countries attaching a higher penalty to untreated infections will be more inclined to impose stricter lockdowns to compensate for lockdown inefficiency.

Substituting the equilibrium lockdown into equations 3.1 and 2.4 yields the corresponding equilibrium outcomes:

(3.7) $$u^* = \frac{(1-\theta)\omega^2}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2}(\nu - \gamma) - \frac{(1-\theta)\omega\lambda\nu}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2}\bar{g}$$

(3.8) $$y^* = \left(\frac{(\lambda-1)\theta\lambda\nu^2 + \theta\lambda\nu\gamma + (1-\theta)\omega(\omega - \bar{g})}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2}\right)\omega$$

The equilibrium level of untreated infections hence depends on fiscal space, while the equilibrium level of production depends on the size of the health system and lockdown compliance. Endowments and mitigation efficiency unambiguously raise a country's welfare, i.e. the more endowments, the lower the social loss.

4. THE LOCKDOWN POLICY RULE UNDER UNCERTAINTY

In his seminal paper on the effect of uncertainty on policy effectiveness, Brainard (1967) outlines how *"optimal policy in presence of uncertainty differs significantly from optimal policy in world of certainty"*. This insight should plausibly also hold for the optimal lockdown policies implemented in response to the COVID-19 outbreak. The "novel" Coronavirus confronted policy-makers with two major types of uncertainty: first, uncertainty around the transmission properties of the virus and the magnitude of the epidemic. Second, uncertainty about the effectiveness of mitigation policies. In the early days of the outbreak, some commentators - and policy-makers - compared the policy endeavours to mitigate the pandemic to a 'war'. To frame the two types of uncertainty within this bellicose analogy, little was known initially about the strength of the enemy, nor about the firepower of the own weapons. This section discusses how the lockdown policy rule and the outcomes are affected when moving from a deterministic set-up to one that is characterised by these two uncertainties.

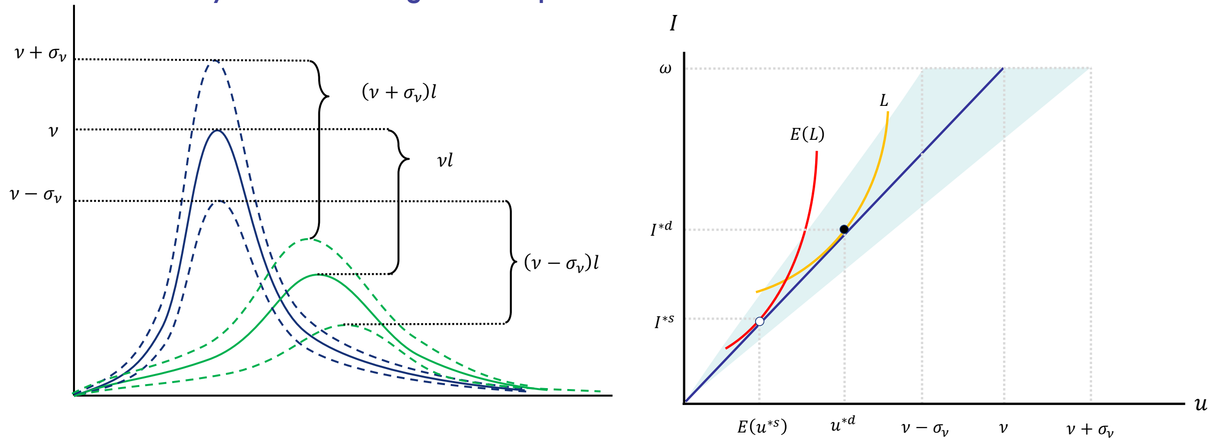
The first uncertainty relates to the magnitude of the epidemic.[19] In particular, the objective to flatten the epidemic curve to a certain level, required lockdown policy decisions to be based on an estimate of the latent number of infections, i.e. an estimated epidemic curve. Indeed, the maximum number of infections would only become observable if no mitigation policies were put in place (and would otherwise remain an unobserved counterfactual).[20] The maximum infections equation (2.1) can accordingly be written in a stochastic form (equation 4.1, where the superscript s refers to stochastic), as the sum of a deterministic part and a mean-zero disturbance with variance σ_ν^2 (Chart 6, left panel).

(4.1) $$\nu^s = \nu + \epsilon_\nu,\ \epsilon_\nu \sim (0, \sigma_\nu^2)$$

[19] In the case of COVID-19, the unknowns relate for example to the existence of pre-existing immunity (Doshi, 2020), the case fatality ratio, the incubation period (i.e. pre-symptomatic infectiousness), the proportion of asymptomatic cases, the duration of infectious period (Anderson et al., 2020), or variants of the virus.

[20] An example it provided by Ferguson et al (2020), who estimated that in a scenario of an uncontrolled pandemic, i.e. in the absence of any mitigating measures, and with an assumed R_0=2.4, 81% of the UK population would be infected during the pandemic, causing approximately 510,000 deaths. At the peak, the demand for ICU or critical care bed demand would exceed supply by a factor 30.

Chart 6: **Uncertainty about the strength of the epidemic**

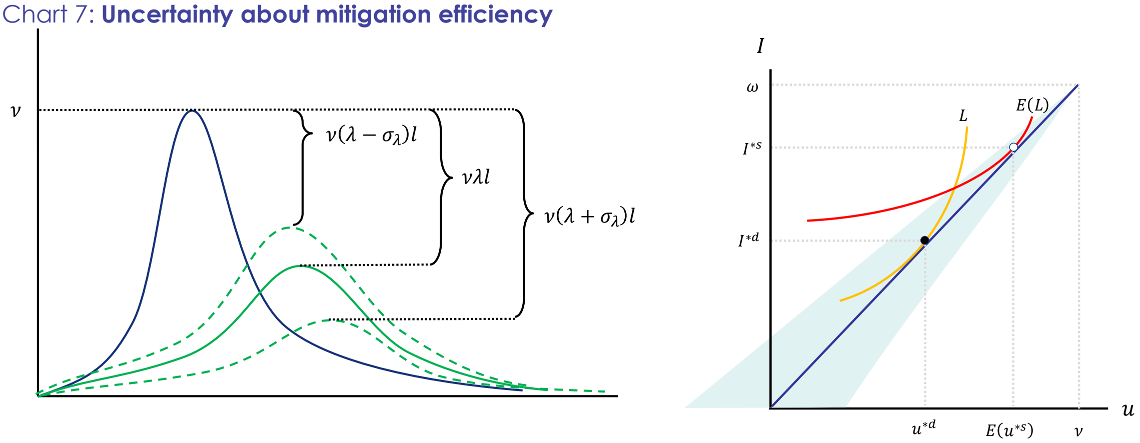


Note: The left chart illustrates uncertainty surrounding the epidemic curve. The right chart illustrates uncertainty about the latent strength of the disease in the form of a one-standard deviation confidence band around the possibility frontier, with $\lambda = 1$. The lockdown is determined by the point of tangency with the expected loss curve (4.6).

The second uncertainty concerns the effectiveness of the instrument, i.e. to what extent the lockdown actually "flattens" the curve. A policy-maker can exert pressure on the epidemic curve by determining the lockdown severity, but may not know with certainty its mitigation efficiency (Chart 7, left panel).[21] The imperfect knowledge about the ultimate impact of the lockdown is reflected in the stochastic version of equation (3.2):

$$\lambda^s = \lambda + \epsilon_\lambda, \epsilon_\lambda \sim \left(0, \sigma_\lambda^2\right) \quad (4.2)$$

Chart 7: **Uncertainty about mitigation efficiency**



Note: The left chart illustrates uncertainty surrounding the efficiency of the lockdown. The right chart illustrates that uncertainty in the form of a one-standard deviation confidence band around the possibility frontier, with $\lambda = 1$. The lockdown is determined by the point of tangency with the expected loss curve (4.6).

It can be further assumed that the two types of uncertainty interrelate, with $E(\epsilon_\nu \epsilon_\lambda) = \sigma_{\nu\lambda} = \rho\sigma_\nu\sigma_\lambda$ and that $\rho \leq 0$. The intuition behind this is that the knowledge about the spread of the virus and its mitigation, respectively, are jointly determined: an underestimation of the magnitude of the epidemic

[21] This relates for example to the epidemiological effects of school closures.

would likely be associated to an overestimation of the effectiveness of mitigating action. Substituting equations 4.1 and 4.2 into 3.1 gives the stochastic version of the latter:

(4.3) $$u^s = \nu^s(1 - \lambda^s l) - \gamma,$$

where

(4.4) $$E(u^s) = u,$$

and

(4.5) $$\sigma_u^2 = \nu^2 l^2 \sigma_\lambda^2 + (1 - \lambda l)^2 \sigma_\nu^2 - 2\nu l(1 - \lambda l)\sigma_{\nu\lambda} + l\sigma_\lambda^2 \sigma_\nu^2$$

u^s is thus a random variable distributed about u. The variance of u^s (given by equation 4.5) depends on the own and joint distributions of ϵ_ν and ϵ_λ, and is dependent on the lockdown intensity. As a result, policy-makers' trade-off is now between I and $E(u^s)$.

These two uncertainties shape the trade-off, albeit in different ways. If the mitigation efficiency parameter λ is fixed and known ($\sigma_\lambda^2 = \sigma_{\nu\lambda} = 0$), the variance of u^s collapses to $\sigma_u^2 = (1 - \lambda l)^2 \sigma_\nu^2$. This implies that σ_u^2 will decline in the stringency of the lockdown and, for $\lambda \geq 1$, converge to zero at $l = 1/\lambda$, thus delivering a certain outcome. The expected possibility frontier remains unchanged, but the confidence band around it narrows as the lockdown intensity increases (Chart 6, right panel). Meanwhile, if there is certainty about the magnitude of the epidemic and ν is known ($\sigma_\nu^2 = \sigma_{\nu\lambda} = 0$), equation 4.5 collapses to $\sigma_u^2 = \nu^2 l^2 \sigma_\lambda^2$. Now $\sigma_u^2 = 0$ at $l = 0$, and increases with the lockdown stringency, reflecting that the mitigating impact of the lockdown is uncertain, i.e. only the absence of a lockdown yields a certain outcome. The confidence band around the expected possibility frontier widens as the lockdown becomes more vigorous (Chart 7, right panel).

What does this imply for the lockdown policy? Essentially, the government now minimises an expected rather than the deterministic social loss function:

(4.6) $$E(L) = \frac{\theta}{2} E(u^2) + \frac{(1 - \theta)}{2} (\tilde{I} - I)^2$$

Taking the first order condition and solving with respect to l yields the optimal lockdown policy under uncertainty

(4.7) $$l^{*s} = \frac{\theta\lambda\nu(\nu - \gamma) + (1 - \theta)\omega\bar{g} + \theta(\lambda\sigma_\nu^2 + (2\nu - \gamma)\sigma_{\nu\lambda})}{\theta\lambda^2\nu^2 + (1 - \theta)\omega^2 + \theta\left(\nu^2\sigma_\lambda^2 + \lambda^2\sigma_\nu^2 + \sigma_\lambda^2\sigma_\nu^2 + 4\lambda\nu\sigma_{\nu\lambda}\right)}$$

Consistent with Brainard's conclusion, the optimal lockdown policy under uncertainty differs from the deterministic policy (equation 3.5) and depends on the respective own and joint distributions of ϵ_ν and ϵ_λ. Again this can be better understood by turning to the two special cases of equation 4.7, in which λ and ν, respectively, are fixed. In the first case, the latent strength of the virus is unknown, while the mitigation effect is known, i.e. $\sigma_\lambda^2 = \sigma_{\nu\lambda} = 0$. The lockdown policy rule now reduces to:

(4.8) $$l^{*s} = \frac{\theta\lambda\nu(\nu-\gamma) + (1-\theta)\omega\bar{g} + \theta\lambda\sigma_\nu^2}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2 + \theta\lambda^2\sigma_\nu^2}$$

It can be shown that in this case $l^{*s} > l^{*d}$,[22] where l^{*d} is the deterministic optimal lockdown given by (3.6). In the second case, the latent strength of the virus is known with certainty, but there is uncertainty about the mitigation transmission, i.e. $\sigma_\nu^2 = \sigma_{\nu\lambda} = 0$, yielding

(4.9) $$l^{*s} = \frac{\theta\lambda\nu(\nu-\gamma) + (1-\theta)\omega\bar{g}}{\theta\lambda^2\nu^2 + (1-\theta)\omega^2 + \theta\left(\nu^2\sigma_\lambda^2\right)}$$

In this case $l^{*s} < l^{*d}$. The lockdown l^{*s} is thus determined at the point of tangency between the expected social loss curve and the possibility frontier (Chart 6, right panel). Uncertainty about u thus has important implications for lockdown policy decisions. As shown in equation 4.8, uncertainty about ν translates into a tighter lockdown relative to the deterministic version. As a result, both the production level and $E(u^s)$ will be lower than in the deterministic version $\left(u^{*d}, I^{*d}\right)$. By imposing a tighter lockdown, the policy-maker will forfeit a higher share of production in return for less uncertainty, as represented by the narrower uncertainty band around $E(u^s)$. The intuition is that while the probability distribution around $E(u^s)$ is symmetric, the associated marginal impact on social loss is asymmetric. A higher than expected u will increase the distance to the target level and entail a higher penalty.[23] The (certain) reduction in income ($I^{*d} - I^{*s}$) is thus akin to an insurance premium. Meanwhile, uncertainty about the effectiveness of the mitigation policy (equation 4.9), will translate into a less vigorous lockdown: a decision-maker who is unsure of the effect of its instrument should rely on it less than it would if it were sure (cf. Brainard's principle of attenuation). In particular, it will be reluctant to sacrifice production the more doubtful the mitigating effect on infections is. Accordingly, both production and $E(u^s)$ will be higher compared to the deterministic setting (Chart 7, right panel). In both cases, policy-makers will have a bias towards less uncertain outcomes, regardless of their preference parameter. Where both uncertainties are present simultaneously, they will work in opposite directions and the ultimate effect on l^{*s} will depend on the dominating one.

Different priors on the distributions of ν and λ would yield different lockdown policies for two economies that are otherwise identical. The views of policy-makers - and/or the epidemiologists advising them – on σ_ν^2 relative to σ_λ^2 could hence constitute a plausible and important explanatory factor behind observed cross-country variation in lockdown intensities. Not taking account of such priors may – erroneously - lead to attributing observed differences in lockdown intensity to differences in preferences. Another implication of decision-making under uncertainty is that an optimal *ex ante* decision, will be sub-optimal *ex post*, as the uncertainties originally factored in by the decision-maker dissipate with hindsight. *Ex post* evaluations of lockdown policies will need to take account of the uncertainty prevailing at the time of the decision and the priors used.[24]

[22] Excluding corner solutions where $l^{*d} = 1$ in cases where $\lambda < 1$.

[23] Given that u is a random variable and the loss function convex, Jensen's inequality implies that, for a given lockdown intensity $E\big(L(u)\big) > L\big(E(u)\big)$, i.e. the loss experienced if the share of untreated patients turns out as expected is lower than the expected loss.

[24] For example, statements by Sweden's State epidemiologist suggest that uncertainty about the mitigation efficiency had indeed shaped decisions, and may thus help to explain the less stringent lockdown during the first wave compared to other European countries. Towards the end of the first wave, he stated that "*based on the*

Given the intense efforts dedicated to better understanding the "novel" coronavirus, it can be assumed that overall uncertainty has declined with time, resulting in more efficient estimates of the latent number of infections and the mitigation efficiency. Uncertainty would thus plausibly be lower for countries benefiting from more preparation time, as earlier virus outbreaks (elsewhere) provide an opportunity to gain knowledge about the virus' propagation and mitigation. To revert to the "war on the virus"-analogy mentioned earlier: preparation time (τ) helps to better "know the enemy" and the own weapons. To illustrate this, assume that $\partial\sigma_v^2/\partial\tau < 0$ and $\partial\sigma_\lambda^2/\partial\tau < 0$, i.e. uncertainty decreases with preparation time. As $\tau \to \infty$, these variances converge to zero, implying that l^{*s} will converge to its deterministic value l^{*d}. Likewise, it can also be shown that $E(L) \to L$, i.e. the additional penalty (insurance premium) due to uncertainty diminishes with time, providing an advantage to countries hit by a later onset. Separately, it would also seem reasonable to imagine that the uncertainty ratio $\sigma_v^2/\sigma_\lambda^2$ could change over time, as uncertainties decline at different paces. Lockdown intensities may thus vary at different stages of the epidemic due to changes in the variance ratio.

5. APPLICATION OF THE MODEL: SEQUENTIAL OUTBREAKS AND VALUE OF PREPARATION TIME

5.1. PREPARATION TIME

As noted in the introduction, the outbreak of the COVID-19 pandemic across countries – both in Europe and globally – occurred in a sequential manner. Early outbreaks in reference countries[25] signalled further imminent ones, implying that some countries had the opportunity to observe and learn from those affected earlier. The first outbreaks hence conferred preparation time to other countries, which increased the later their position in the outbreak sequence. Many countries used that time to pre-empt the domestic outbreak by imposing restrictions before witnessing critical infection numbers (Chart 2). This "head start" on the virus can potentially contribute to explain the observed cross-country variation in lockdown intensities and outcomes. In the context of COVID-19, it is plausible that even a few days of preparation prior to the onset have been valuable, for a number of reasons:

- *Political economy and lockdown acceptance*: One important effect of the lockdowns implemented by the countries first hit was simply to render them imaginable elsewhere and to demonstrate their legitimacy as tools to mitigate epidemics. In connection with images and information authenticating the severity of COVID-19, notably relating to the rising death toll

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knowledge we had then, we feel we made the appropriate decisions." He further stated that "[other] countries started with a lot of measures all at once," judging that "[the] problem with that is that you don't really know which of the measures you have taken is most effective." The implication is that "[if] we were to encounter the same disease again, *knowing exactly what we know about it today*, I think we would settle on doing something in between what Sweden did and what the rest of the world has done" (interviews with 'Sverige Radio' and 'Dagens Nyheter', as reported in Habib (2020); emphases added).

[25] The reference country here means the first country hit in the region in which a country is located. In Europe, the reference country would be Italy, which was the first country to suffer the virus outbreak. The main argument for a regional focus is that an outbreak in a neighbouring country represents a stronger signal for an imminent domestic outbreaks. Even where public authorities had started to prepare following outbreaks in countries located in other regions (e.g. China or Iran), the preparations only accelerated only once the virus arrived in Europe. While the model could accommodate different "initial outbreaks", this would not add much value from a conceptual point of view and the focus is thus on the first outbreak on the continent.

and overwhelmed health care systems,[26] they contributed to familiarise initially unaffected populations with the "inevitability" of the eventual need to rely on lockdowns. As such, it can be plausibly considered that the first outbreaks, and in particular the outbreak in the north of Italy, have altered personal and societal threat perceptions with respect to COVID-19 elsewhere, and prepared the ground for swift and more widely endorsed lockdowns elsewhere.[27] In many European countries affected by later outbreaks, there was broad-based and cross-party support for (at times) very stringent lockdowns (e.g. in Belgium a new government was formed with the specific mission to manage the period of the Coronavirus outbreak).

- *Design of lockdown and compensation measures*: a later outbreak provided time to prepare the entire policy response package, i.e. legislate on and communicate about the different aspects of the lockdowns (cancellation of events, school closures, etc.), possibly already making them more targeted. Further, it provided time to design the compensation measures to cushion the economic shock (e.g. job-retention schemes, loan moratoria, etc.).
- *Health care capacity and medical knowledge:* in many countries, the COVID-19 outbreak threatened to overwhelm health care systems and required emergency upscaling to deal with the surge in patients. This was often achieved by freeing capacity allocated to non-COVID patients or the establishment of temporary "field" hospitals for both COVID and non-COVID patients, e.g. in sports arenas or exhibition centres. Countries hit at a later stage had more possibilities to increase their surge capacity or to adjust emergency plans in anticipation of the outbreak. In addition, they could benefited from more advanced medical knowledge and were better prepared to receive and treat patients.
- *Uncertainty about the virus and about the effectiveness of mitigation measures*: all governments faced the double uncertainty on latent infections and the impact of mitigation measures (cf. section 4). It seems again plausible that the first outbreaks provided data and evidence that reduced these uncertainties.

Preparation time, τ, enters the model via two channels: through a mark-up on the mitigation efficiency, and an expansion of the initial treatment capacity at a rate z, resulting in a health system that is able to provide treatment to a share m of the population at the onset of the disease. This is represented as follows:

(5.1) $\lambda = (1+\delta)(1+\tau)$, where $\tau \geq 0$

(5.2) $m = (1+z\tau)\gamma$

[26] Initially, COVID-19 was sometimes presented as a form of seasonal flu, primarily affecting older persons with medical preconditions. Views on shutting down the economy because of a flu and shutting it down because of a deadly virus are likely to differ.

[27] A central political economy problem arises when there are implementation costs arising in the short term that are certain and concentrated, while the benefits only arise in the long term and are uncertain and diffused. A median voter would oppose a policy under such circumstances. This also applies to lockdowns implemented in reaction to the Coronavirus outbreak: while their costs are known and direct, the benefits, i.e. avoided infections, are harder to pinpoint (it is impossible to determine precisely who would have been infected in a counterfactual no-lockdown scenario). It can however be assumed that the median voter's cost-benefit assessment has evolved as the public health consequences of virus outbreaks elsewhere became more evident.

Mitigation efficiency (5.1) now depends on two factors: lockdown adherence and preparation time. The two factors differ in their nature, with the former being a country-specific characteristic, while the latter is a pure windfall benefit. The possibility frontier (3.4) and the equilibrium lockdown (3.6) equations remain unchanged, except for m, which is substituted for γ.

Diagrammatically, preparation time can be represented by the possibility frontier swinging out clockwise (higher λ) and shifting to the left (higher m) (Chart 8). The impact on social loss is given by

(5.3) $$\frac{\partial L}{\partial \tau} = \theta u \left(\frac{\partial u}{\partial \lambda} \frac{\partial \lambda}{\partial \tau} + \frac{\partial u}{\partial l} \frac{\partial l}{\partial \tau} + \frac{\partial u}{\partial m} \frac{\partial m}{\partial \tau} \right) + (1-\theta)(\tilde{I} - I) \left(\frac{\partial y}{\partial l} \frac{\partial l}{\partial \tau} \right) < 0$$

Social loss thus necessarily declines with preparation time. Using the fact that at the welfare maximising equilibrium $\partial L / \partial l|_{l^*} = 0$, and substituting for the other differentials, this reduces to

(5.4) $$\left. \frac{\partial L}{\partial \tau} \right|_{l^*} = -\theta u^* \big((1+\delta) l^* + z\gamma \big),$$

highlighting that the impact of preparation time on social loss will depend on country characteristics. Countries with a high lockdown compliance (δ) and a higher capacity to expand their health system (z), will benefit most from preparation time ($\partial L / \partial \tau \partial \delta < 0$ and $\partial L / \partial \tau \partial z < 0$). Furthermore, preparation time is more valuable for countries that have a high loss parameter associated to untreated infections ($\partial L / \partial \tau \partial \theta < 0$). Finally, the marginal decline in social loss will be higher for countries with a high equilibrium number of untreated infections and stringent lockdowns ($\partial L / \partial \tau \partial u^* < 0$ and $\partial L / \partial \tau \partial l^* < 0$).

As follows from section 3, the maximum lockdown, i.e. $l^{UB} = (\nu - m)/\lambda \nu$, will decline as preparation time raises mitigation efficiency, while the effect on the optimal lockdown intensity ($\partial l^* / \partial \tau$) is ambiguous and will depend on the increase in mitigation efficiency and the health system capacity as a result of preparation time.[28] With preparation time $\tau \geq \tau^g$, where $\tau^g = (\omega(\nu - \gamma) - (1+\delta)\nu \bar{g}) / (\omega z \gamma - (1+\delta)\nu \bar{g})$, the available fiscal space would allow compensating entirely for the foregone production, while reducing untreated infections to zero, i.e. $u^*(\tau^g) = 0$.

5.2. PRICING PREPARATION TIME

Writing the loss function as $L(\tau, g)$, a country experiencing an outbreak of the epidemic without preparation time, $\tau = 0$, will experience a social loss given by $L_0 = L^*(0, \bar{g})$. For the country to experience a lower loss, L_1, it would need either preparation time, $\Delta\tau$, such that $L_1 = L^*(\Delta\tau, \bar{g})$, or additional fiscal space, Δg, such that $L_1 = L^*(0, \bar{g} + \Delta g)$. The marginal effect of a change in g on L is given by

(5.5) $$\frac{\partial L}{\partial \bar{g}} = \theta u \left(\frac{\partial u}{\partial l} \frac{\partial l}{\partial \bar{g}} \right) - (1-\theta)(\tilde{I} - I) \left(\frac{\partial y}{\partial l} \frac{\partial l}{\partial \bar{g}} + \frac{\partial \bar{g}}{\partial \bar{g}} \right) < 0$$

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[28] $z > 0$ implies that with a sufficiently long preparation time, the health care capacity would ultimately be in a position to provide treatment to all infected persons. This would be the case for $\tau \geq \tau^z$, where $\tau^z \geq (\nu - \gamma)/z\gamma$, at which point there would be no lockdown, i.e. $l^*(\tau^z) = 0$, and no fiscal transfers would be required, as production would be at its potential level, i.e. $y^*(\tau^z) = \omega$. Furthermore, there would be no social loss, i.e. $L(\tau^z) = 0$.

Social loss thus declines with fiscal space. Using again the fact that at equilibrium $\partial L/\partial l|_{l^*} = 0$, this reduces to

(5.6) $$\left.\frac{\partial L}{\partial \bar{g}}\right|_{l^*} = -(1-\theta)(\tilde{I} - y^* - \bar{g}).$$

A marginal increase in fiscal space would be more valuable for countries with a low θ and those with low equilibrium production and low initial fiscal space. The change in social loss following marginal increases in preparation time and fiscal space, respectively, can thus be approximated by

(5.7) $$L^*(\Delta\tau, \bar{g}) - L^*(0, \bar{g}) \approx \frac{\partial L^*(0, \bar{g})}{\partial \tau}\Delta\tau$$

and

(5.8) $$L^*(0, \bar{g} + \Delta g) - L^*(0, \bar{g}) \approx \frac{\partial L^*(0, \bar{g})}{\partial \bar{g}}\Delta g$$

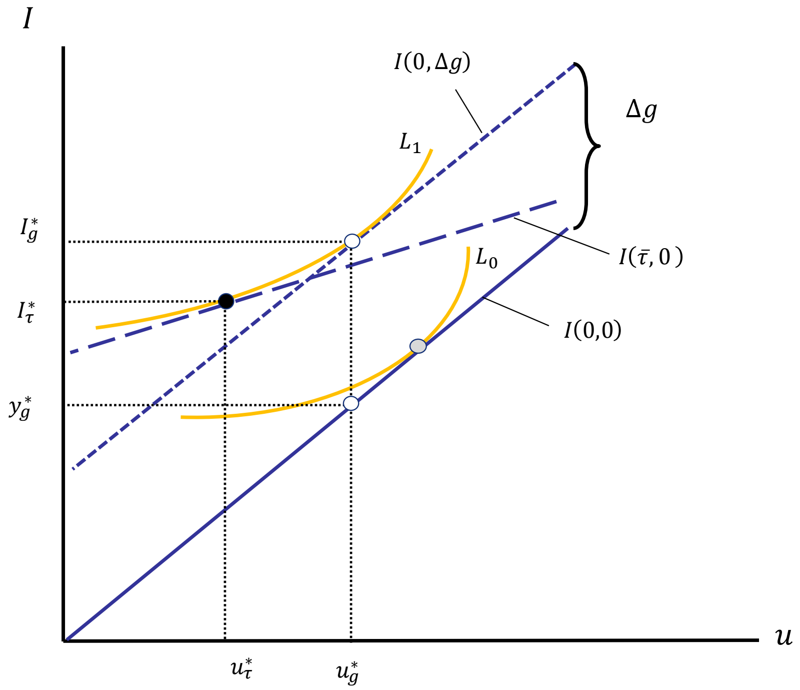
Given that $L^*(\Delta\tau, \bar{g}) = L^*(0, \bar{g} + \Delta g)$, and using equations 5.4 and 5.6, one can solve for Δg:

(5.9) $$\Delta g = \frac{\theta u^*\big((1+\delta)l^* + z\gamma\big)}{(1-\theta)(\tilde{I} - y^* - \bar{g})}\Delta\tau.$$

Δg corresponds to the equivalent variation, i.e. the additional amount of fiscal space that would have been required in the absence of preparation time to lower the social loss by an equivalent amount as preparation time did (by yielding higher mitigation efficiency and a higher health care capacity). Preparation time is a pure windfall benefit and Δg in equation 5.9 attaches a monetary value to it. Clearly, this value is country-specific and determined by endowments and preferences.[29] For a given preparation time, the fiscal equivalent will be higher for countries with high lockdown compliance, as well as for countries with a high u^*, and low y^* or $\bar{g}$. The monetary value of preparation time increases in the weight assigned to untreated infections (θ).

[29] While the model treats the endowments as being exogenous, it is important to acknowledge that they reflect past policy-decisions and shocks. However, this does not invalidate the fact that preparation time constitutes a windfall gain.

Chart 8: **Preparation time versus increase in fiscal space (equivalent variation)**



Note: The chart illustrates how preparation time and additional fiscal space, respectively, can have an equivalent effect on social welfare for a country that initially has neither.

Note that while the social loss would in both cases be the same (L_1), the optimal lockdown and respective outcomes would differ (Chart 8). Additional fiscal space would increase the affordability of a lockdown and the move from L_0 to L_1 would hence imply a tighter lockdown. The lower production revenue (y_g^*) would be offset by the fiscal transfer (Δg). Meanwhile, attaining L_1 through preparation time would loosen the lockdown, implying higher production ($y_\tau^* = I_\tau^*$). In terms of outcomes, income (including the transfer), but also the number of untreated infections would be higher in the scenario with additional fiscal space than in the scenario with preparation time, i.e. $I_g^* > I_\tau^*$ and $u_g^* > u_\tau^*$.

5.3 IMPLICATIONS IN A MULTI-COUNTRY CONTEXT

What does this imply in a multi-country setup? While preparation time reduces a country's social loss, preparation time only exists because of the sequential - rather than synchronised - nature of the outbreak. Being hit first, country i is caught unprepared, but provides the signal for preparations to start in country j.[30]

The loss experienced by country j can be decomposed in two terms:

(5.10) $$L^j(\tau) = L^j(0) - \pi^j(\tau)$$

the first term, $L^j(0)$, is a constant and corresponds to the loss that would have arisen in the counterfactual scenario in which the country had been the first one to experience the outbreak. The

[30] That signal requires that the information about the outbreak has the characteristics of a public good, i.e. it is non-rival and non-excludable.

second term, $\pi^j(\tau)$, represents the value of preparation time, which corresponds to $\frac{\partial L}{\partial \tau}\Big|_{l^*} \Delta\tau$, and is increasing in τ, with $\pi^j(0) = 0$. This bonus captures the positive externality provided, albeit involuntarily, by country i to country j.

Note that both $L^j(0)$ and $\pi^j(\tau)$ are country-specific, and will depend on country j's characteristics. This can be illustrated by considering two countries, A and B, where the former has a larger health system and can rely on higher lockdown compliance, i.e. $\gamma_A > \gamma_B$ and $\delta_A > \delta_B$, and which are identical otherwise. At $\tau = 0$, country A would register a lower social loss than country B. With preparation time of length $\tau = \bar{\tau}$, social loss would necessarily decline for both countries. The time bonus would however be bigger for A, reflecting a larger (absolute) expansion in its health care capacity (due to z) and a higher mitigation efficiency, allowing it to make better use of preparation time.

As the example illustrates, the outbreak sequence matters from a joint perspective. The combined social loss would be highest with a synchronised outbreak at $\tau = 0$ ($L_A^*(0) + L_B^*(0)$), and would be lowest under a sequential scenario in which country B was hit first ($L_A^*(\bar{\tau}) + L_B^*(0) < L_A^*(0) + L_B^*(\bar{\tau})$). The outbreak sequence hence has implications for post-pandemic country divergence. In this example, both countries start out with the same economic potential and would have the same production in the absence of the outbreak. Thanks to higher endowments of γ and δ, country A is better positioned to use, and possibly preserve, its economic potential than country B in the event of an epidemic. Importantly, in this example, the resulting economic (income) divergence does not result from the structure or size of the economy, but from countries' ability to address the outbreak by exploiting their health care systems or ensuring lockdown compliance.

As regards the outbreak of COVID-19 in Europe, the information about the early outbreaks had public good character and allowed other countries to prepare.[31] The sequential nature of the outbreak thus makes it distinct from a symmetric shock, given that the initial outbreak, which was akin to a stochastic idiosyncratic shock, created value elsewhere. This inherent shock absorption also distinguishes it from a pure asymmetric shock (e.g. an earthquake) that would have no direct effect on other countries. The country-specific positive externality (cf. equation 5.9), would justify some form of transfer from later hit countries to those that have, albeit unintentionally, endowed them with preparation time.[32]

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[31] As a thought exercise, one could imagine a hypothetical market-mechanism: if the information about an outbreak were excludable, i.e. a private rather than a public good, a market for that information could be established, with (first hit) country i as a seller and (later hit) country j as a potential buyer of that information. Indeed, without knowledge of an imminent outbreak, no preparation trigger would exist. Country i could (partially) offset its social loss, while country j would benefit from preparation time that would guarantee it a social loss reduction of $\pi^j(\tau)$. Effectively, this would amount to splitting $\pi^j(\tau)$, which would be Pareto-efficient and make both countries better off.

[32] Implicitly, this is achieved by the recovery and resilience facility (RRF) set-up by the European Union in response to the pandemic, as the associated grants are allocated on the basis of the economic impact of the pandemic, which is inversely linked to preparation time (see annex). The RRF will provide grants and loans to EU Member States. Grants will be distributed according to two allocation mechanisms: 70 % will be allocated based on pre-pandemic country characteristics (population, GDP per capita, and the average unemployment rate). The remaining 30 % will take into account the observed loss in real GDP in 2020 and the observed cumulative loss in real GDP over the 2020-2021 period. In addition, the EU's temporary 'support to mitigate unemployment risks in an emergency' (SURE) provides financial assistance to Member States in the form of loans to help them address the negative economic and social consequences of the pandemic.

6. GENERALISED LOCKDOWN VERSUS TARGETED MEASURES

The framework developed in sections 2 and 3 has considered general non-targeted lockdowns of a fraction l of the population. While general and indiscriminate lockdowns have characterised the initial reaction to the outbreak, they have been complemented progressively by more refined NPIs that target the transmission of the virus with a minimal adverse impact on the labour force and production. The possibility to resort to targeted measures however varies and may thus contribute to explain country variation in lockdowns and outcomes. Four types of targeted measures are illustrated in turn: 1) working from home; 2) closure of contact-intensive sectors; 3) confinement of risk groups; 4) testing, contact-tracing and isolation-schemes. This section builds on the baseline version of the model presented in section 2, i.e. no endowments and no focus on mitigation efficiency of general measures ($\bar{g}, \gamma$ and $\delta = 0$).

6.1. WORKING FROM HOME

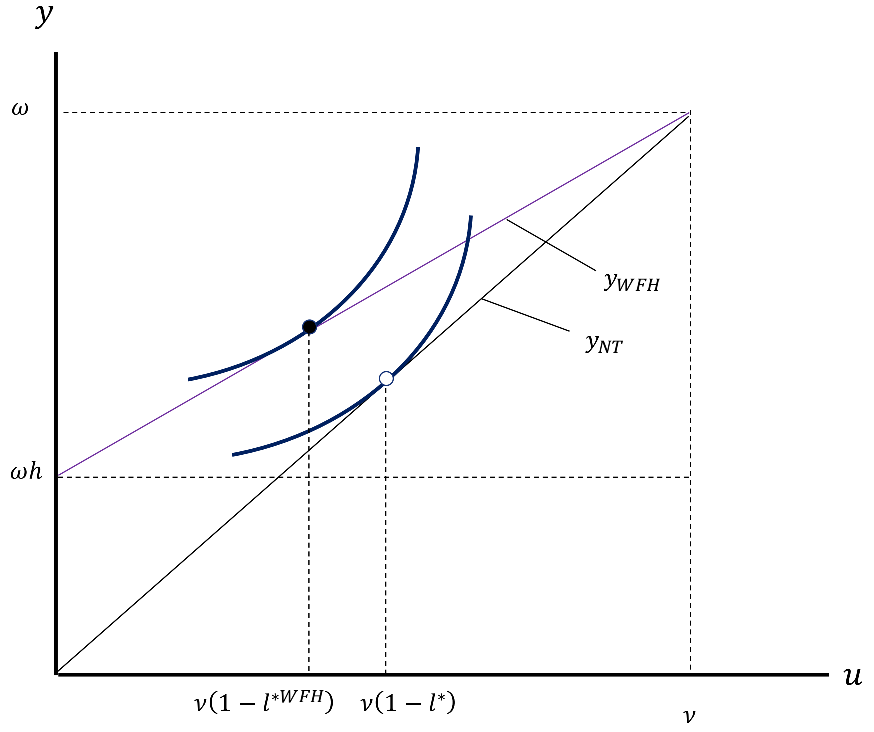
Working from home (WFH) has become a widespread (recommended or mandatory) working arrangement during the pandemic, enabled or facilitated by information and communications technology. Sostero et al. (2020) and Dingel and Neiman (2020) both estimate that 37% of jobs in the EU and in the United States, respectively, can be performed remotely from home.[33] WFH effectively renders the fraction of production that can be carried out from home 'lockdown immune', i.e. it excludes it from the production-infections trade-off. If the share of the workforce that can work from home is given by $h \leq (1-\alpha)$, the lockdown production function (2.4) can be rewritten as $y_{WFH} = \omega h + \omega(1-h)(1-l)$.[34] Even under a total lockdown, production can thus not fall below ωh. Assuming that there are no costs related to WFH[35], the possibility frontier becomes $y_{WFH} = \frac{\omega(1-h)}{\nu}u + \omega h$, implying that the possibility set rotates clockwise about bundle (ν, ω), making the country unambiguously better off (see Chart 9). The optimal lockdown will be given by the following rule:

(6.1)
$$l^{*\mathrm{WFH}} = \frac{\theta\nu^2}{\theta\nu^2 + (1-\theta)\omega^2(1-h)^2} + \frac{(1-\theta)\omega^2 h}{\theta\nu^2 + (1-\theta)\omega^2(1-h)^2}$$

The possibility of working from home hence implies a stricter general lockdown, i.e. $l^{*\mathrm{WFH}} > l^*$. Nonetheless, this will result in both lower infections and higher output compared to a situation where WFH is not possible. Countries with economic structures allowing for remote work are thus better placed to absorb the adverse impact of an epidemic. This also implies that a high general lockdown stringency is not necessarily indicative of the magnitude of economic loss.

[33] As both papers show, there is significant geographical and sectoral variation. In particular, the share of jobs that can be carried out from home is positively related to GDP per capita and thus higher in advanced and lower in developing and emerging market countries (Dingel and Neiman, 2020).
[34] This framework could also include industrial sectors that can continue operating because they do not involve close physical contact.
[35] It is acknowledged that productivity may differ - for example when telework has to be combined with childcare, following school and crèche closures - and workplace-specific positive externalities may be lost. In addition, there may be fixed costs related to setting up remote work infrastructures.

Chart 9: **Working from home**



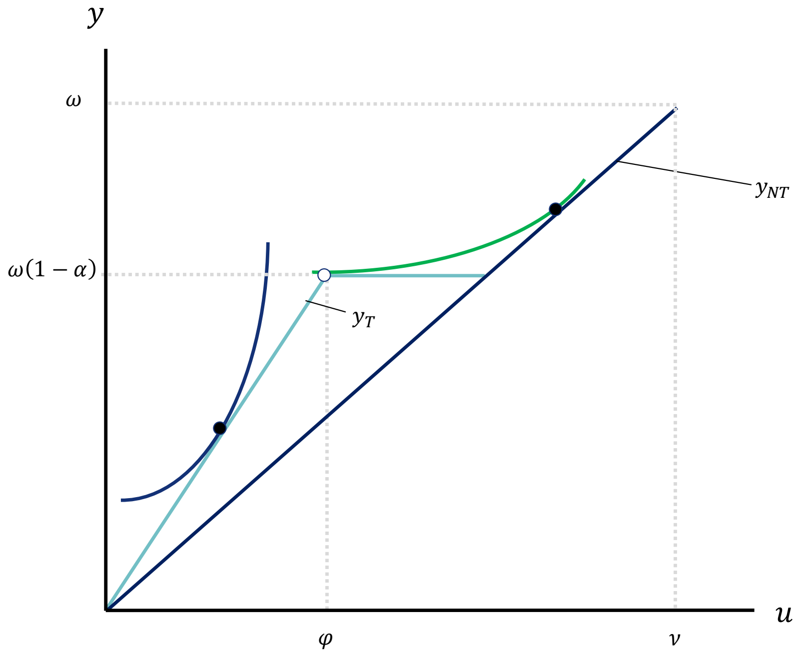
6.2. CLOSURE OF CONTACT-INTENSIVE SECTORS

A targeted sectoral lockdown, consisting in shutting down the contact-intensive sectors α, is equivalent to changing a country's economic structure for the time of the epidemic. This has two effects: first, it reduces the size of the economy, i.e. maximum production in the absence of a general lockdown falls to $y = \omega(1-\alpha)$; second, it reduces the latent severity of the epidemic, i.e. $\nu = \varphi$, as the negative externality emanating from contact-intensive sectors is removed.

With the targeted measure in place, the possibility frontier is now given by $y_T = \frac{\omega(1-\alpha)}{\varphi} u$. In addition, the country still has the option to select a point on its general, non-targeting, possibility frontier (2.5). Superposing the targeted and general possibility sets, gives rise to a nonconvex (kinked) possibility set. That implies that a country will have more options among which it can choose. However, it will not necessarily opt for targeted measures, as its choice will depend on social preferences. Countries where $l^{*NT} \geq \alpha$, will necessarily opt for a combination of a target sectoral closure and a general lockdown of the 'restructured' economy (chart 10, blue line). This condition is less likely to be met by countries with a high α/θ ratio.[36] Indeed, countries with a high share of contact-intensive sectors or a strong preference for preserving production, i.e. $\theta \leq \theta^{low}$, are more likely to favour a non-targeted (and loose) lockdown (chart 10, green line). For example, in a country living exclusively of tourism (with $\alpha = 1$), a targeted closure would be equivalent to a total closure of the economy (a full generalised lockdown could otherwise only happen when $\theta = 1$).

[36] While α is presented primarily as a country-specific feature in this paper, it may also have a significant seasonal dimension. For example, even within a country, α may be higher during sales or in the pre-Christmas period, affecting the decision of whether or not to apply targeted measures.

Chart 10: **Closure of contact-intensive sectors**



6.3. PROTECTION OF RISK GROUPS THROUGH TARGETED CONFINEMENTS

Another type of targeted measure is to focus on population characteristics that determine the latent strength of the epidemic, φ, but do not affect y. This would for example be the case for the targeted protection through social distancing of older age cohorts[37] or groups belonging to high-risk category as regards COVID-19 (cf. Acemoglu et al. (2020)).[38] Analogously to the change in the economic structure discussed above, the targeted confinement in this model would be akin to a temporary (for the duration of the epidemic) modification of the population structure.

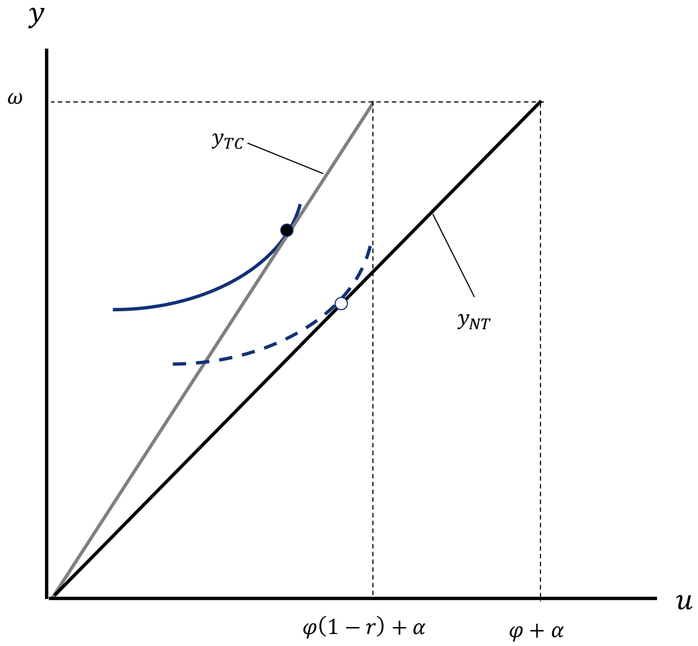
If risk groups account for a share r of the population, their targeted confinement would lower the latent infection number to $\nu = \varphi(1-r)+\alpha$. Assuming that persons in risk groups are not part of the working population and there are no production-related costs associated to such a targeted confinement,[39] the possibility frontier would rotate anti-clockwise around the point of origin (chart 11) and be given by $y_{TC} = \frac{\omega}{\varphi(1-r)+\alpha}u$. The targeted confinement (as described here) would hence be equivalent to a cost-free weakening of the epidemic, making the country unambiguously better off.

[37] For example, the study by Ferguson et al. (2020) assumes a case fatality ratio 0.15% for the 40-49 age group, which rises to 2.2% (60-69), 5.1% (70-79) and 9.3% (80+). The higher vulnerability of older adults is also reflected in the high proportions of infections and fatalities in long-term care homes. Using a sample of 21 advanced economies, Comas-Herrera et al. (2020) report that the share of COVID-19 deaths that were care home residents, averages 46%, ranging from 8% (South Korea) to 81% (Slovenia). The authors note, however, that these figures are subject to difficulties arising from differences in definitions.

[38] The European Centre for Disease Prevention and Control defines high-risk groups for COVID-19 as i) People aged 60 years and older; ii) those living in long-term care facilities; and iii) people with underlying health conditions, such as hypertension, diabetes, cardiovascular disease, chronic respiratory disease and weakened immune systems (https://www.ecdc.europa.eu/en/covid-19/high-risk-groups).

[39] If individuals in the risk group were part of the workforce, a targeted confinement would imply an adverse effect on production and give rise to a nonconvex possibility set, akin to the targeted lockdown of contact-intensive sectors in the example above. Separately, it is noted that targeted confinements may entail psychological and well-being costs that are not captured in this model.

Chart 11: **Targeted confinement of risk groups**



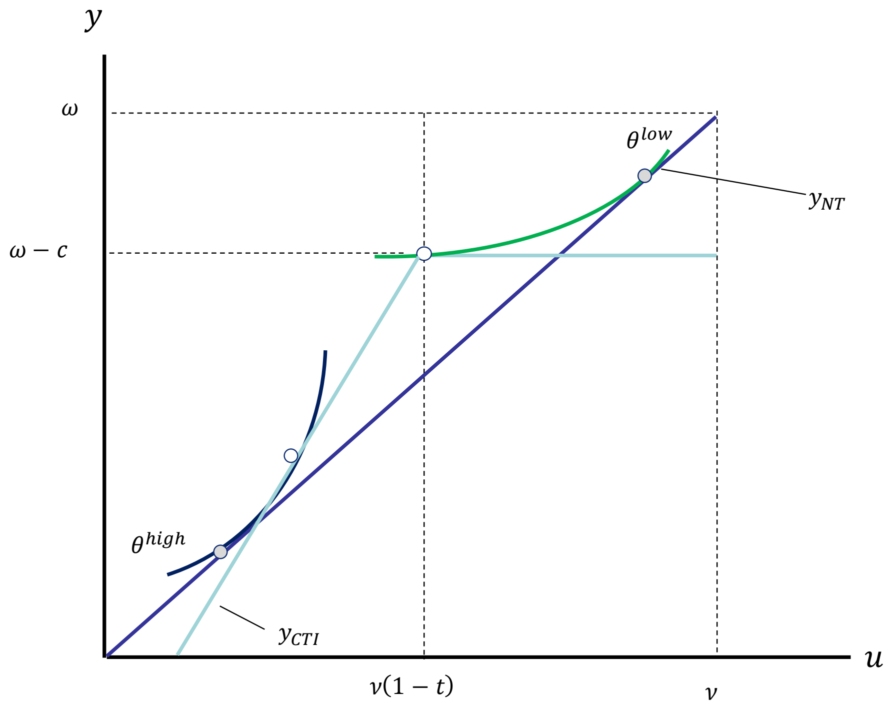
6.4. TESTING, CONTACT-TRACING AND ISOLATION

It is assumed that by testing the population and isolating persons that are infected or have been in contact with an infected person, the latent strength of the epidemic can be brought down by a share t to $\nu(1-t)$ (see also Aum, Lee and Shin (2020)). While it is assumed that this does not affect production, implementing a testing scheme however comes at a fixed cost, c, directly reducing income. As a result, the possibility frontier, now given by $y_{CTI} = \frac{\omega}{\nu(1-t)}u - c$, rotates anti-clockwise around the origin and shifts downwards (chart 12). With a contact-tracing system in place and absent of any general lockdown, income will be given by $\omega - c$, for $\nu(1-t)$ untreated infections.

The choice to implement a testing scheme will depend on its cost-efficiency and social preferences. With a cost-efficiency ratio $c/t < \omega$ (as in the chart 12), the superposition of the targeted possibility set will give rise to a kinked possibility frontier. For a cost-efficiency ratio $c/t > \omega$, the targeted possibility set will be inside the general one, implying that the scheme will not be worthwhile.[40] A country will opt for a contact-tracing and isolation scheme as long as its preferences are given by $\theta \in [\theta^{low}; \theta^{high}]$. Countries with more extreme preferences will continue to opt for a generalised lockdown.

[40] Note that costs can be interpreted quite widely. The technologically most advanced tracing-app would have a prohibitive cost to society, if concerns about privacy, say, deter people from installing it.

Chart 12: **Testing, contact-tracing and isolation**



Overall, the illustrations of these four targeted measures show that both the economic and human loss can be lowered jointly with respect to optimal uniform policies. Relative to generalised lockdowns, they increase possibilities and change the nature of the trade-offs. As these new possibility sets are in many cases nonconvex, it will however depend on countries' preferences and the potential offered by targeted measures, whether they will adopt them - on their own or in combination with a generalised lockdown. Again, these differences may explain the uneven adoption of targeted measures across countries and, by extension, differences in outcomes.[41]

7. CONCLUSION

This paper proposes a simple stylised model to explain and illustrate why lockdown decisions and outcomes may vary across countries. In particular, it presents the nature of the trade-off between the preservation of production and income on the one hand, and the minimisation of untreated infections on the other, as a function of fundamental factors (fiscal space, health system capacity, sectoral structure of the economy), behavioural characteristics (lockdown compliance) and preparation time. Preparation time represents a windfall benefit allowing for a more timely and effective reaction to the outbreak of a disease. The model also illustrates how, in a context of uncertainty, the priors of policy-makers and epidemiologists affect lockdown decisions relative to a deterministic setting. Finally, it shows how the nature of the trade-off changes, when there is the possibility to introduce targeted measures.

[41] Separately, they also illustrate the multifaceted and complex nature of dealing with the pandemic and the resulting difficulty of summarising the lockdown intensity in a single index that can be used to explain cross-country divergences in both economic contraction and strength of the pandemic, respectively.

The model considers the epidemic as a single event. Its static and linear nature implies some limitations, as it does not capture the non-linear patterns that characterise the propagation of the disease and the effect of lockdowns on production, respectively. However, it provides a tractable and intuitive framework that helps to structure arguments that are more complex, notably by using comparative statics. These can notably be helpful in explaining individual lockdown decisions and country differences.

Although the model primarily tries to explain variations in lockdown intensity and outcomes across countries as a function of country characteristics, there are nonetheless some important policy implications both at individual country level and collectively. First, endowments invariably reduce the social loss generated by an epidemic. However, these endowments vary in their nature and may be either tangible, such as the size of the health care system or fiscal space, or intangible, as is the case for many factors determining lockdown compliance. This result is also a reminder of the broad nature of the "fundamentals" that underpin economic resilience. Second, specific endowments affect production and infections, respectively, in different ways. Likewise, their effect on lockdown policies, which may become either looser or stricter, varies. Third, the possibility of implementing targeted measures increases a country's possibility set. By providing additional options to a country, they potentially reduce social loss and allow to simultaneously lower infections and output losses. However, their implementation is not certain and depends on country-characteristics and preferences. Fourth, the *ex post* evaluation of lockdown policies needs to take account of the uncertainty prevailing at the time lockdown decisions were taken, as choices may otherwise seem sub-optimal with hindsight.

The model has further policy-relevant implications from a multi-country perspective. First, variations in endowments imply differences in the ability to deal with infections and may affect and possibly exacerbate economic divergence. Secondly, in the case of a sequential outbreak of the epidemic, joint social costs are lower than under a synchronised outbreak. The reason is that the first outbreak provides a positive externality to other countries in the form of preparation time, which mitigates their social loss. This preparation time has value and its provision would justify some compensation to the first countries hit in view of mitigating their social loss.

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ANNEX: EMPIRICAL SUPPORT

The objective of this annex is to provide empirical support to the theoretical model developed in this paper. A key feature of the theoretical model is the importance of preparation time, which is assumed to increase mitigation efficiency and thereby safeguard GDP and lives. This annex examines its role in explaining the observed variation in GDP contraction and fatality rates in 2020, when controlling for other factors.

The variables included in the analysis are listed in table A.1 below and summary statistics displayed in table A.2. A number of variables in the theoretical model are unobserved. This is notably the case for social preferences and for the latent strength of the epidemic, which is proxied by pollution, density, age structure and the case fatality ratio, which is however subject to idiosyncrasies in counting. Lockdown compliance is imperfectly proxied by indicators of trust. The sample covers all EU Member States, with the exception of Malta, as well as Norway, Serbia, Switzerland and the United Kingdom. Besides the small sample size, additional caveats relate to existing intra-country variation in infections and mitigation policies. Consequently, the estimates should be interpreted with care.

Table A.1: **Variables and data sources**

Variable	Description	Source
Growth	Annual percentage change in GDP (Modified Domestic Demand for Ireland).	Eurostat, Central Bank of Ireland
PT_cases	Preparation time: number of days between the outbreak of the disease in Italy (first country affected) and the outbreak in a given country. The outbreak is dated at 100 confirmed cases.	Hale et al. (2020)
RRT_cases	Relative reaction time: number of days between the outbreak of the disease in Italy (first European country) and the imposition of stay at home requirements in a given country. The date of the imposition of generalised stay at home requirements is determined when the C6 indicator (Record orders to "shelter-in-place" and otherwise confine to the home) is at or above 2 (2: require not leaving house with exceptions for daily exercise, grocery shopping, and 'essential' trips; 3: require not leaving house with minimal exceptions (e.g. allowed to leave once a week, or only one person can leave at a time, etc.)), and the measure is applied country wide (C6_Stay at home requirements (>=2)* C6_Flag).	Hale et al. (2020)
Alpha	Share of contact-intensive sectors (‘Accommodation and food service activities’, ‘Travel agency, tour operator and other reservation service and related activities’ and ‘Arts, entertainment and recreation’) in total value added, 2019 or latest observation available (2017 or 2018)	Eurostat
Debt	Public debt-to-GDP ratio, 2019 (Fiscal space (inverse measure))	Eurostat
HCE	Capacity of health system: proxied by current health care expenditure per person in EUR, 2018 (MT and NL: 2017)	Eurostat
Over_65	Share of population over 65, 2018	Eurostat
Pollution	Exposure to air pollution by particulate matter, 2018	Eurostat
Density	Persons per square km, 2018	Eurostat
Trust_polsyst	Degree of trust in political system, 2013	Eurostat
Trust_others	Degree of trust in others, 2013	Eurostat
Victims	Total number of victims per 100 000 inhabitants up until 30/06/2020 and 31/12/2020, respectively.	Hale et al. (2020)
CFR	Case fatality ratio: number of deaths from disease as a share of the number	Hale et al.

	of confirmed cases of disease, up until 30/06/2020. Measures the severity among detected cases.	(2020)

Table A.2: **Summary statistics of variables used**

variable	N	mean	sd	min	max
Growth_20	30	-4,970268	2,700757	-10,96315	-,7707642
Growth_19	30	2,456923	1,278955	,284185	4,749271
victims_HY1	28	20,27674	23,58672	,5137218	84,03809
victims_FY	29	72,97203	39,8716	8,182858	170,468
PT_cases	30	17,23333	7,393769	0	29
PT_victims	30	28,76667	13,76573	0	62
RT_cases	27	4,481481	8,395834	-9	19
RT_victims	27	-10,74074	14,82096	-48	11
RRT_cases	27	22	6,557439	8	37
Alpha	30	,0464782	,0202668	,0221352	,0899498
Density	30	130,1367	108,4819	17,2	504
Over_65	29	19,21379	2,12934	14,1	22,8
HL_65	29	9,017241	2,906651	4,4	15,7
Debt	30	63,15333	36,91388	8,4	176,6
HCE	30	2880,094	2085,97	583,95	8327,38
Trust_pols~t	30	3,883333	1,358012	1,7	6,6
Trust_others	30	5,823333	,9167722	4,2	8,3
CFR	30	6,584524	4,685579	1,681682	18,14988

GDP contraction

Following equations 2.9 and 3.8, GDP growth in 2020 is regressed on preparation time (τ), the share of contact-intensive sectors (α), public debt ($\bar{g}$) and health expenditure (γ), as well as some controls that proxy for mitigation efficiency and the latent strength of the epidemic (x). GDP growth in 2019 is also included. The estimated ordinary least squares model is of the form:

(A.1) $$Growth(2020)_i = c + \beta_0 Growth(2019)_i + \beta_1 \tau_i + \beta_2 \alpha_i + \beta_3 \bar{g}_i + \beta_4 \gamma_i + \beta_* x_i$$

Table A.3: **Regression results – GDP contraction, 2020**

	(1) Growth_20 b/t	(2) Growth_20 b/t	(3) Growth_20 b/t	(4) Growth_20 b/t	(5) Growth_20 b/t	(6) Growth_20 b/t	(7) Growth_20 b/t	(8) Growth_20 b/t
Growth_19	-0,394	0,059	0,156	0,139	0,172	0,140	0,376	0,405
	(-0,98)	(0,15)	(0,43)	(0,38)	(0,50)	(0,38)	(1,04)	(0,94)
PT_cases	0,221***	0,211***	0,240***	0,239***	0,217***	0,242***	0,169**	0,180**
	(3,22)	(3,48)	(4,05)	(3,90)	(3,81)	(4,07)	(2,55)	(2,34)
Alpha	-84,353***	-53,310***	-51,664***	-50,296***	-38,405**	-49,732***	-57,503***	-54,243***
	(-4,82)	(-3,00)	(-3,08)	(-3,03)	(-2,29)	(-2,87)	(-3,65)	(-3,11)
Debt		-0,018	-0,020*	-0,020*	-0,013	-0,020*	-0,012	-0,010
		(-1,59)	(-1,93)	(-1,90)	(-1,28)	(-1,91)	(-1,10)	(-0,80)
HCE		0,001**	0,001***	0,001***	0,000*	0,001***	0,001***	0,001***
		(2,45)	(3,13)	(3,29)	(2,03)	(3,27)	(3,51)	(3,03)
Over_65			0,308*	0,294*	0,231	0,298*	0,280*	0,261
			(1,97)	(1,85)	(1,54)	(1,90)	(1,95)	(1,63)
Pollution			0,028					
			(0,50)					
Density				-0,000				
				(-0,15)				
Trust_polsyst					0,551*			
					(1,78)			
Trust_others						0,025		
						(0,08)		
CFR							-0,148*	-0,133
							(-1,93)	(-1,53)
RRT_cases								-0,023
								(-0,49)
Constant	-3,891***	-6,582***	-14,683***	-13,593***	-14,591***	-13,928***	-11,914***	-11,646**
	(-3,23)	(-3,33)	(-3,18)	(-3,06)	(-3,64)	(-2,96)	(-2,94)	(-2,58)
R-squared	0,586	0,743	0,797	0,795	0,822	0,795	0,826	0,812
adj. R-squared	0,539	0,689	0,730	0,727	0,763	0,727	0,768	0,724
p	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Countries	30,000	30,000	29,000	29,000	29,000	29,000	29,000	26,000

* p<0.10, ** p<0.05, *** p<0.01

The estimates for different model specifications are displayed in table A.3. Overall, the model explains the observed variation in GDP growth reasonably well and many of the estimated coefficients on the main independent variables are significant and have the expected sign. Importantly and in support of the theoretical model, preparation time is significant and positive in all specifications: an additional week of preparation time, when determining the date of the outbreak on the basis of registered infections, would imply 1.2-1.7 percentage points ($\widehat{\beta_1} * 7$) higher annual GDP growth.[42] This is in the same order of magnitude as in Demirgüç-Kunt et al. (2020), who find that countries that implemented lockdowns one week prior to the first reported COVID-19 death saw a decrease in economic activity (proxied by electricity consumption) that was about 2% smaller in countries that implemented a lockdown on the day of the first death. Note that the significance found here may also capture the fact that a later outbreak may imply less days in lockdown. Accounting for the relative reaction time (specification 8), i.e. number of days between the outbreak in Italy and the stay-at-home order (where applicable) in the different countries, indeed somewhat reduces the size and statistical significance of the coefficient on preparation time. Meanwhile, α has a negative effect that is significant in all specifications and confirms a country's vulnerability to an epidemic resulting from its economic structure: an additional percentage point in the value added share of contact-intensive sectors would lower growth by about 0.5 percentage points. Health expenditure per capita has a significant positive effect, supporting the view that bigger health systems cushion the economic impact of an epidemic. Public debt, density and trust measures generally have the expected signs, but are not statistically significant. The share of population above 65 positively affects growth but is not statistically significant. The positive coefficient is surprising given that age is an individual risk factor. At the macro-economic level, however, this positive impact likely reflects the fact that persons in this age

[42] Setting preparation time to zero for all EU countries covered – as would have been the case with a pure synchronised shock - would suggest a combined GDP decrease in the range of 7.6% to 8.4% (specification 6), instead of the recorded 6.2%.

category are typically retired. As such, there is no production activity that the lockdowns would prevent them from engaging in. The case fatality ratio, which is included as a gauge for the severity of the epidemic (specifications 7 and 8), has a negative and significant coefficient, i.e. the stronger the epidemic, the larger the economic loss.

COVID-19 fatalities

The second set of regressions is based on equations 2.8 and 3.7. Whereas the focus of the theoretical model is on "untreated infections", the dependent variable used here is the number of COVID-19 deaths in 2020 relative to the population. It should be noted that the counting of COVID-19 victims has been subject to discussions and there have been differences in counting practices, which possibly explain some of the observed cross-country variation, including the outlier status of some countries. In analogy to equation A.1, the following model is estimated:

$$\text{(A.2)} \qquad Victims\ (end\ 2020)_i = \mathrm{c} + \beta_1\tau_i + \beta_2\alpha_i + \beta_3\bar{g}_i + \beta_4\gamma_i + \beta_*\mathrm{x}_i$$

Table A.4: **Regression results – COVID-19 fatalities, 2020 (full year)**

	(1) victims_FY b/t	(2) victims_FY b/t	(3) victims_FY b/t	(4) victims_FY b/t	(5) victims_FY b/t	(6) victims_FY b/t	(7) victims_FY b/t
PT_cases	-1.627	-2.764*	-2.882**	-2.961*	-3.127**	-2.505	-3.639**
	(-1.60)	(-1.98)	(-2.35)	(-2.03)	(-2.25)	(-1.64)	(-2.62)
Alpha	90.665	7.194	415.722	382.446	192.012	352.169	403.869
	(0.25)	(0.02)	(0.99)	(0.86)	(0.44)	(0.79)	(0.96)
Debt		-0.017	-0.261	-0.241	-0.228	-0.229	-0.472
		(-0.06)	(-1.00)	(-0.88)	(-0.88)	(-0.83)	(-1.71)
HCE		-0.007	-0.009**	-0.009*	-0.004	-0.009*	-0.010*
		(-1.60)	(-2.14)	(-1.98)	(-0.79)	(-2.00)	(-2.07)
BE			108.627***	106.636**	95.751**	89.969**	105.782**
			(2.87)	(2.70)	(2.53)	(2.11)	(2.89)
Over_65				-0.976	-0.422	-0.296	-0.124
				(-0.25)	(-0.11)	(-0.07)	(-0.03)
Pollution					2.610*		
					(1.85)		
Density						0.076	
						(1.02)	
RRT_cases							1.140
							(1.04)
Constant	96.293***	141.951***	140.631***	163.599	92.183	134.143	152.878
	(3.86)	(3.34)	(3.77)	(1.65)	(0.91)	(1.30)	(1.61)
R-squared	0.091	0.189	0.403	0.401	0.488	0.431	0.506
adj. R-squared	0.021	0.054	0.273	0.230	0.309	0.231	0.302
p	0.288	0.265	0.028	0.069	0.037	0.084	0.059
Countries	29.000	29.000	29.000	28.000	28.000	28.000	25.000

* p<0.10, ** p<0.05, *** p<0.01

Overall, the explanatory power of the model is comparatively weak (cf. table A.4) and only becomes more meaningful once a dummy is included for Belgium (specifications 3 to 7), which is an outlier. Preparation time is negative and weakly significant in most specifications. An additional week of preparation time would have reduced the number of deaths per 100 000 inhabitants in 2020 between 18.9 and 26.6 (specifications 2 and 8). COVID-19 deaths decline in health expenditure and increase in pollution, as expected and have generally weakly significant coefficients. The coefficients on density, public debt and the share of over 65 year old persons in the overall population are not statistically significant.

Re-estimating the model for the first half of 2020 (up to 30/06/2020), covering the "first wave" of the COVID-19 pandemic, alters the results somewhat (cf. table A.5). The fit improves, notably when including the dummy for Belgium, and preparation time is negative and significant in all specifications. Health expenditure, density and debt generally have the expected signs, but are not statistically significant. Pollution and the share of persons older than 65 years have an unexpected negative and statistically significant coefficient.

Table A.5: **Regression results – COVID-19 fatalities, 2020 (first half year)**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	victims_HY1	victims_HY1	victims_HY1	victims_HY1	victims_HY1	victims_HY1	victims_HY1
	b/t	b/t	b/t	b/t	b/t	b/t	b/t
PT_cases	-2.192***	-2.004***	-2.099***	-2.673***	-2.694***	-2.619***	-2.685***
	(-4.79)	(-2.99)	(-3.71)	(-4.36)	(-4.72)	(-3.96)	(-4.98)
Alpha	-12.132	-120.824	93.077	123.754	255.684	119.179	75.135
	(-0.07)	(-0.57)	(0.48)	(0.66)	(1.37)	(0.62)	(0.46)
Debt		0.109	-0.027	-0.009	-0.070	-0.005	0.030
		(0.77)	(-0.21)	(-0.07)	(-0.59)	(-0.04)	(0.28)
HCE		0.000	-0.001	-0.002	-0.006**	-0.002	-0.002
		(0.04)	(-0.38)	(-1.19)	(-2.28)	(-1.16)	(-1.01)
BE			54.933***	52.121***	59.625***	50.239**	48.979***
			(3.21)	(3.17)	(3.78)	(2.74)	(3.44)
Over_65				-3.318*	-3.469**	-3.249*	-3.734**
				(-2.02)	(-2.27)	(-1.91)	(-2.59)
Pollution					-1.370*		
					(-2.01)		
Density						0.008	
						(0.26)	
RRT_cases							0.388
							(0.91)
Constant	57.722***	52.188**	53.197***	128.714***	169.559***	125.381**	126.197***
	(5.15)	(2.48)	(2.99)	(3.13)	(3.91)	(2.85)	(3.42)
R-squared	0.479	0.494	0.656	0.709	0.760	0.710	0.801
adj. R-squared	0.437	0.407	0.577	0.622	0.672	0.603	0.719
p	0.000	0.003	0.000	0.000	0.000	0.000	0.000
Countries	28.000	28.000	28.000	27.000	27.000	27.000	25.000

* p<0.10, ** p<0.05, *** p<0.01

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