Cost-benefit analysis of age-specific deconfinement strategies

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Abstract

I calibrate a Multi-Risk SIR model on the covid pandemic to analyze the impact of the age-specific confinement and PCR testing policies on incomes and mortality. Two polar strategies emerge as potentially optimal. The suppression policy would crush the curve by confining 90% of the population for 4 months to eradicate the virus. The flatten-the-curve policy would reduce the confinement to 30% of the population for 5 months, followed by almost one year of free circulation of the virus to attain herd immunity without overwhelming hospitals. Both strategies yield a total cost of around 15% of annual GDP when combining the economic cost of confinement with the value of lives lost. I show that hesitating between the two strategies can have a huge societal cost, in particular if the suppression policy is stopped too early. Because seniors are much more vulnerable, a simple recommendation emerges to shelter them as one deconfines young and middle-aged people in order to build our collective herd immunity. By doing so, one reduces the death toll of the pandemic together with the economic cost of the confinement, and the total cost is divided by a factor 2. I also show that expanding the mass testing capacity to screen people sent back to work has a large benefit under various scenarios. This analysis is highly dependent upon deeply uncertain epidemiologic, sociological, economic and ethical parameters.

Keywords: Covid, pandemic, PCR test, confinement, value of life, SIR, flatten the curve.

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1 Introduction

Because the covid-19 pandemic has huge economic consequences, it makes sense for economists to explore the dynamics of this virus with the aim of searching for efficient public policies. This reminds me what economists have been able to do in the field of climate economics over the last four decades. I am neither an epidemiologist nor a climatologist, but I believe that combining these fields with economics is important for the policy debate, given the key issue of the economic cost of fighting the coronavirus or climate change.

In this paper, I explore a Multiple-Risk Susceptible-Infected-Recovered (MR-SIR) model with heterogeneous citizens. People differ by their age, by the intensity of their social interactions, by their ability to transmit the virus, and by their probability to be hospitalized or to die. If infected, they can be symptomatic or not. Their reproduction rate is a function of whether they are quarantined, confined or freed to live their life. PCR tests can be used to detect infected people among the population of apparent susceptible people (asymptomatic contagious people belong to this category). In my model, individual reproduction numbers, and therefore the dynamics of the pandemic, depend upon the implemented public policy in terms of the intensity of confinement and PCR testing, which can be age-specific. I compare the merits of different intuitive public policies.

It is by now well recognized that the laissez-faire strategy is not an efficient solution, given the high mortality rate of SARS-Cov-2 compared to the standard flu. With a herd immunity attainable only with a rate of immunity around 80% and a mortality rate around 1%, this strategy would kill 0.8% of the population, not taking account of the excess mortality due to the overcrowding of hospitals under this scenario. In the absence of treatment or vaccine, two families of health policies remain, the "suppression" (or "crush-the-curve") strategy and the "flatten-the-curve" strategy. Suppression policies consist in imposing various rules such as strict social distancing, mass testing, confinement of susceptible people and quarantine of contagious people, with the aim to reduce the reproduction number as much as possible below unity to crush the curve of infection. To illustrate, China has implemented such a strategy around Wuhan, and Italy, Spain and France have used similar strategies until early May 2020. Because the dynamics of the pandemic has an exponential nature, following such a strategy until the full eradication of the virus in the population may takes time that most pandemic models measure in months if not in years. The economic cost of the suppression strategy could therefore be huge. The termination of the pandemic also requires a specific method (testing-and-tracing) to eliminate the last clusters of infection.

The "flatten-the-curve" strategy consists in imposing much weaker restrictions in order to reduce the speed of propagation of the virus so that the initial wave of infection is manageable by the health care system. This is because the ICU capacity is limited, and its overcrowding is known to dramatically increase the infected-fatality ratio of the pandemic. Stabilizing the flow of hospitalizations requires a weaker confinement than in the suppression strategy, and is therefore less economically costly. Under this family of policies, the population converges towards herd immunity, whose level depends upon the intensity of the social restrictions. At some date along this asymptotic herd immunity, the prevalence rate will become so small that eradication can also be obtained with some form of testing-and-tracing method. In spite of the preservation of the health-care system, flatten-the-curve strategies are expected to impose a much larger death toll to the population since it requires that a large fraction of the population to be infected sometimes during the pandemic.

Age Class	Prob[hospitalized if infected]	Prob[deceased if infected]
0-18	0.10%	0.001%
19-64	2.00%	0.15%
65+	12.27%	3.65%

Table 1: Estimation of the hospitalization rate and of the infection-fatality proportion by age class in France. Source: Saltje et al. (2020) and INSEE.

To sum up, compared to crush-the-curve strategies, flattening the curve typically yields more lives lost but a smaller GDP loss. Comparing the two families of policies from a welfare point of view thus requires valuing lives. Within economics, this is a relatively consensual issue. Outside economics, valuing lives is vastly rejected, in spite of the fact that public institutions have been using a "value of statistical life" for at least four decades in the Western world.[1] In this paper, I follow the traditional approach used by health and environmental economists in which health effects of the public policies under scrutiny are translated into income equivalent. I discuss this specific issue in the context of the current pandemic in Gollier (2020).

A striking feature of covid-19 is its huge differential health impact on human being across different age classes, as shown in Table 1 for the case of France. If the objective is to minimize the death toll or to make sure hospitals are not submerged, it is tempting to protect senior people from the virus. The problem is that doing so marginally increases the mortality risk for the younger generations, thereby raising the question of the relationship between the value of life and age. In this paper, I value life to 60 years, 40 years and 20 years of annual GDP/cap respectively for the young, middle-aged and senior people. I show that a strict lockdown of the most vulnerable persons in our society during the most active phase of the pandemic is an efficient policy to reduce both the death toll and the economic cost of the pandemic, independent upon whether one pursue the suppression or the flatten-the-curve objective.

A few recent papers have supported similar age-targeted deconfinement strategies. Acemoglu, Chernozhukov, Werning and Whinston (2020) characterize two intertemporally optimal exit strategies from lockdown, one in which the policy is constrained to be uniform across age classes, and the other in which different age classes can be treated in a discriminated way. They claim that 2.7 million lives could be saved in the United States by maintaining a stricter confinement for the seniors.[2] Favero, Ichino and Rustichini (2020) compare different age-specific policies for Italy and come to the same conclusion of the overwhelming dominance of confining elderly people longer. Fischer (2020) and Wilder et al. (2020) also support a strong sheltering of the vulnerable persons. Brotherhood, Kircher, Santos and Tertilt (2020) explore the impact of various confinement policies on the incentive of different age classes to behave efficiently. All those models share the same fundamental structure of the MR-SIR framework that I use in this paper.

[1] For more information, see for example Drèze (1962), Schelling (1968), Jones-Lee (1974), Shepard and Zeckhauser (1984), Murphy and Topel (2006), Viscusi (2009), US-EPA (2010) and Quinet (2013).

[2] The paper of Acemoglu et al. (2020) has the great advantage to describe the Pareto frontier of efficient policies. In this paper, I don't search for an intertemporally optimal solution, but I compare different intuitive strategies that have been used, or are expected to the used in the future.

What did I learn from this analysis beyond the high social value of discriminating the intensity of the confinement across different age classes? Several things in fact. First, I learned that in the family of reasonable policies, there exists two polar solutions, one with strong restrictions with the objective to crush the curve as soon as possible, and another one with much milder restrictions just to flatten the curve. Under the calibration of my MR-SIR model, the suppression strategy necessitates confining 90% of the entire population for 125 days. The flatten-the-curve strategy imposes the confinement of 30% of the entire population for six months, followed by almost a year of a low level of the virus prevalence in the population. These two very different strategies yields a similar total cost around 15% of annual GDP, which combines the economic cost of the confinement and the value of lives lost.

Second, the planner should be strong in her policy choice. Hesitation and trembling hand can have a high welfare cost. To illustrate this point, suppose that the country initially plan to follow the suppression strategy of confining 90% of the population during 125 days. But suppose that it changes her mind after t days of strong confinement to follow the flatten-the-curve strategy in which only 30% of the population remains confined until herd immunity. Figure **??** shows the relationship between the duration of the suppression strategy and the total cost of the pandemic. For a zero duration, we have the best flatten-the-curve policy, and for a 125-day duration, we have the best suppression strategy. But stopping short of the 125-day duration of the suppression policy will generate a high-cost second wave of the pandemic. I describe this dynamic in Figure 1 in the Appendix when abandoning the suppression policy after 95 days, one month short of what is necessary to eradicate the virus. Switching to the flatten-the-curve strategy a few days short of the 125 days dramatically increases the total cost of the pandemic, which increases from 15% of annual GDP to around 24%, because of the second wave of infection that this "trembling hand" policy generates.

Third, because of the coexistence of these two polar policies yielding similar total costs, an important international coordination problem emerges. If all countries select the suppression strategy except one which follows the flatten-the-curve strategy, this contrarian country will impose a huge negative externality on the international community. Indeed, the suppression strategy has this weakness to converge to a low rate of immunization, far away from the herd immunity level in the absence of social distancing. Therefore, because flattening the curve implies a much longer duration of the pandemic, the contrarian country imposes to other countries the risk to export the virus, triggering a new worldwide wave of the pandemic. The absence of coordination implies that countries implementing stronger confinement and quarantine rules will have to limit their interactions (trade, human mobility) with other countries, yielding potentially high additional costs that I do not count in this paper.

Fourth, I characterize the tradeoff between the strength and the duration of the confinement. In the family of flatten-the-curve policies, stricter confinement rules delay the herd immunization and increases the duration of the pandemic. In the family of suppression policies, stricter confinement rules speed up the eradictation of the virus and reduce the duration of the pandemic. Thus, the relationship between the intensity of the confinement and the duration of the pandemic is hump-shaped. This observation has important policy implications. In particular, when implementing the suppression strategy, the stricter the confinement rules the better.

Fifth, there is an obvious point to be made on the dominance of the mass testing strategy over the mass confinement strategy, as claimed at the beginning of the pandemic by the World Health Organization ("Test, test, test!").[3] When the prevalence rate is 2%, it makes little sense to confine everyone, just to make sure that these 2% will have a small reproduction rate. If one could test all people exiting from lockdown, we could reduce the propagation of the virus without imposing the huge cost of freezing the economy. I make this important point in Section 7, since my model is able to simulate the impact of uniform or age-specific testing strategies.

This pandemic simulation exercise heavily relies on the implicit assumptions of the MR-SIR model and on the calibration of its parameters. Thus, my analysis is not more reliable than the estimation of the epidemiologic, sociological, ethical and economic parameters that feed it. As I write this paper, the uncertainty that surrounds many of these parameters should impose circumspection. Who knows the rate of asymptomatic cases, the mortality rate for the young, the immunization of the recovered, the impact of the weather, or the date of arrival of a mass vaccine? This paper, as most others on the same subject, is based on the absurd assumption of known parameters. My agenda in climate economics over the last two decades has been to determine the impact of the uncertainty surrounding the parameters of climate integrated-assessment models on the optimal climate policy. My agenda for the next two months is to do the same thing for the covid policy, based on the uncertainty-free model presented in this paper.

2 The MR-SIR model

In the spirit of Acemoglu et al. (2020) and Favero et al. (2020), I examine a simple SIR model with multiple classes of individuals. The whole population is partitioned in J classes $j \in \{1, ..., J\}$. The size of class j is denoted N_j. In this paper, I partition the population by age classes, since age is an important characteristics that influence the covid mortality risk and the intensity of social interactions. Each person is either Susceptible, Infected, Recovered or Death, i.e., the health status of a person belongs to $\{S, I, R, D\}$. This implies that $S_{j,t} + I_{j,t} + R_{j,t} + D_{j,t} = N_j$ at all dates $t \geq 0$, where $S_{j,t}$ for example measures the number of persons in class j that are susceptible at date t. The total number of infected persons in the whole population at date t is denoted $I_t = \sum_j I_{j,t}$, and similarly for S_t, R_t and D_t. Although, there is no certainty about this aspect of the covid pandemic at this stage, I assume that recovered people are immunized. They are also all detected as such at no cost.

A susceptible person can be infected by meeting an infected person. Following the key assumption of all SIR models, this number of new infections is assumed to be proportional to the product of the densities of infected and susceptible persons in the population, weighted by the intensity of their social interaction. Using the Multi-Risk (MR) version of SIR modeling, and with no further justification, this is quantified as follows:

$$S_{i,t+1} - S_{i,t} = -\left(\sum_{j=1}^{J} \beta_{ijt} I_{j,t}\right) S_{i,t}. \tag{1}$$

I will soon describe how β_{ijt}, which measures the intensity of the risk of contagion of a

[3] https://www.reuters.com/article/us-healthcare-coronavirus-who/test-test-test-who-chiefs-coronavirus-message-to-world-idUSKBN2132S4

susceptible person in class i by an infected person in class j at date t, is related to the social interactions between these two groups and by the confinement and testing policy. Once infected, a person of class i quits this health state at rate γ_i, so that the dynamics of the infection satisfies the following equation:

$$I_{i,t+1} - I_{i,t} = \left(\sum_{j=1}^{J} \beta_{ijt} I_{j,t} \right) S_{i,t} - \gamma_i I_{i,t}. \tag{2}$$

There are two exit doors to the infected status: One can either recover or die. The mortality rate among the infected persons of class i at date t is denoted π_i. It may be a function of the total number of infected people in the whole population. So, we have

$$R_{i,t+1} - R_{i,t} = (1 - \pi_i(I_t))\gamma_i I_{i,t} \tag{3}$$

$$D_{i,t+1} - D_{i,t} = \pi_i(I_t)\gamma_i I_{i,t}. \tag{4}$$

The pandemic starts at date $t = 0$ with ϵ_j infected persons and $N_j - \epsilon_j$ susceptible persons in class j, $j \in \{1, ..., J\}$.

Consider an infected person in class j. How many persons will he infect in period $[t, t+1]$? The answer is $\sum_i \beta_{ijt} S_{i,t}$. Because on average such a person remains infected during $1/\gamma_i$ periods, we can conclude that the reproduction number in class j at date t equals

$$\Re_{jt} = \frac{\sum_{i=1}^{J} \beta_{ijt} S_{i,t}}{\gamma_j}. \tag{5}$$

A fraction κ_j of the infected people in class j are asymptomatic. In the absence of PCR test, they cannot be identified within the population $\hat{S}_{j,t} = S_{j,t} + \kappa_j I_{j,t}$ of "apparently susceptible" persons in class j. All symptomatic persons are quarantined, whereas all recovered persons are freed from any constraint. What about the apparently susceptible persons? I examine two policy instruments. A fraction a_{jt} of $\hat{S}_{j,t}$ is PCR tested. I assume no error in the test. People tested positive are quarantined, whereas the others are freed from any constraint for period $[t, t+1]$. Another fraction b_{jt} remains confined during that period. The remaining fraction $1 - a_{jt} - b_{jt}$ is freed from any lockdown constraint during the period in spite of their uncertain health state. As in Acemoglu et al. (2020), I assume that the confinement is imperfect in the sense that a fraction $1 - \theta_j$ of the confined people in class j ignores the constraints. As a consequence, among susceptible persons in class i, the true number of susceptible persons in that class who behave as confined is $\theta_i b_{it}$ at date t. Among the infected persons in class j at date t, a proportion

- $\kappa_j a_{jt} + 1 - \kappa_j$ is quarantined;
- $\kappa_j \theta_j b_{jt}$ is effectively confined;
- $\kappa_j(1 - a_{jt} - \theta_j b_{jt})$ is freed from the lockdown, or behaves in that way.

The intrinsic degrees $(\beta_q, \beta_c, \beta_f)$ of contagion of an infected person depends upon whether she is quarantined (q), confined (c) or freed (f), with $\beta_q < \beta_c < \beta_f$. Let α_{ij} denote the relative intensity of social interactions between a susceptible person of class i and an infected person of class j. Thus, the intensity of the contagion of a susceptible person in class i by an infected person in class j at date t equals

$$\beta_{ijt} = \alpha_{ij}\Big(\beta_q(\kappa_j a_{jt} + 1 - \kappa_j) + \beta_c \kappa_j \theta_j b_{jt} + \beta_f \kappa_j (1 - a_{jt} - \theta_j b_{jt})\Big)(1 - \theta_i b_{it}) \tag{6}$$

For example, in the laissez-faire policy ($a = b = 0$), all susceptible persons work, together with all asymptomatic infected persons, whereas the symptomatic ones are quarantined. Thus, equation (6) this simplifies to

$$\beta_{ijt} = \alpha_{ij}(\beta_q(1 - \kappa_j) + \beta_f \kappa_j). \tag{7}$$

An important feature of equation (6) is that the intensity of the contagion between age classes i and j is a quadratic form of the confinement intensities b_i and b_j. In the case of a uniform confinement rule, the intensity of contagion is quadratic in the intensity b of confinement. This is due to the fact that the lockdown reduces the interaction from both sides, infected and susceptible.

How can we compare different policies in relation to their welfare impacts? Two dimensions should be taken into account. First, life is valuable, so death has a welfare cost. Let me associate a cost ℓ_j to the death of a person in age class j. The pandemic has also an economic cost associated to the deaths, quarantines, confinements and testing during the pandemic. I assume that quarantined people are unable to work. A fraction ξ_j of confined people in class j can telework. The value loss of a person in class j that cannot work is denoted w_j. For workers, w_j can be interpreted as their labour income. For young people, it's the lost human capital due to the reduced quality of their education during lockdown. For the retired people, it's the value of their contributions to the common good. We must also take account of the economic cost of mass testing. In total, assuming a unit cost of PCR test equaling p, the economic loss of the pandemic in class j is measured as follow:

$$\begin{aligned} W_j = p\int_0^T a_{jt}\hat{S}_{j,t}dt + w_j\Big((1-\xi_j)\int_0^T b_{jt}S_{j,t}dt \\ + \int_0^T (\kappa_j(a_{jt} + (1-\xi_j)b_{jt}) + 1 - \kappa_j)I_{j,t}dt + \int_0^T D_{j,t}dt\Big), \end{aligned} \tag{8}$$

where T is the time horizon of the social planner, for example the discovery of a vaccine or a treatment. The total loss is thus equal to

$$L = \sum_{j=1}^{J} \Big(\ell_j D_{j,T} + W_j\Big). \tag{9}$$

A key dimension of the health policy during a pandemic is the risk of overcrowding the health care system facing limited capacities in beds, ICUs or respirators for example. I summarize this capacity problem by a capacity limit on covid beds in hospitals. I assume that a fraction $h_j < 1 - \kappa_j$ of infected people in class j faces an acute version of the virus and requires a bed to receive an efficient health care. If the overall bed capacity $\overline{h}$ is not overwhelmed, then the mortality rate among infected people in class j is limited to π_{0j}. But of hospitals are overcrowded, then this mortality rate jump up to $\pi_{1j} > \pi_{0j}$:

$$\pi_j(I_{1t}, ..., I_{Jt}) = \begin{cases} \pi_{0j} \text{ if } \sum_i h_i I_{it} \leq \overline{h}, \\ \pi_{1j} \text{ if } \sum_i h_i I_{it} > \overline{h}. \end{cases}$$

Finally, I assume that the pandemic can be obliterated by an aggressive testing-and-tracing strategy if the global infection rate in the whole population goes below some threshold I_{min}.

3 Calibration of the MR-SIR model

Many of the parameters of this model remain highly uncertain, so caution should remain a cardinal virtue when interpreting its results. I consider a daily frequency for this analysis, and I calibrate the model on French data. There are $J = 3$ age classes, young (0-18), middle-aged (19-64), and senior (65+). I normalize the French population of 67 million people to unity. The size of the population in the different age classes is $N = (0.227, 0.568, 0.205)$. At date $t = 0$, we assume that 1% of the population is infected, uniformly across all age classes. I also assume the arrival of a vaccine 1.5 years after the beginning of the pandemic. The minimum rate of infection below which the virus can be obliterated in the population is assumed to be $I_{min} = 0.05\%$.

To simplify the calibration and given the limited available data, I assume that recovery rates, asymptomatic rates, contagion rates, and telework rates are assumed to be age-independent. The daily recovery rate $\gamma_i = \gamma = 1/18$ is assumed to be the same across age classes. This corresponds to the observation that infected people remain sick for 2 or 3 weeks on average. I also assume that the daily contagion rate under business-as-usual is 0.6, and that this rate goes to $\beta_q = 0$ for quarantined people, which is compatible with a basic reproduction number $R_0 = 2.5$ in the absence of policy. In the case of confinement, the contagion rate is equal to $\beta_c = 0.1$. As I write this paper, the rate of asymptomatic cases is particularly difficult to calibrate. The Center for Evidence-Based Medicine has estimated this rate somewhere between 5% and 80%.[4] He, Lau, Wu et al. (2020) found a 95% confidence interval of $[25\%, 69\%]$ for the proportion of asymptomatic cases. More recently, the US Center for Disease Control and Prevention (CDC) has edicted 5 scenarios of the pandemic with two plausible levels of the rate of asymptomatic, 0.2 and 0.5, with a central assumption at 0.35.[5] I assumed a $\kappa = 35\%$ rate of asymptomatic people. The social contact matrix across age classes has been estimated in France by Béraud, Kazmercziak, Beutels, Levy-Bruhl, Lenne, Mielcarek et al. (2015). We approximate their results by the following contact matrix:

$$\alpha_{..} = \begin{pmatrix} 2 & 0.5 & 0.25 \\ 0.5 & 1 & 0.25 \\ 0.25 & 0.25 & 0.5 \end{pmatrix} \tag{10}$$

Social interactions go down with age, within and across age classes. From this set of information, I can estimate the reproduction number at date 0 for the three age classes in the absence of any public policy by using equations (5) and (7). It yields

$$\Re_{y0} = 2.99 \quad \Re_{m0} = 2.77 \quad \Re_{s0} = 1.14. \tag{11}$$

[4]https://www.cebm.net/covid-19/covid-19-what-proportion-are-asymptomatic/

[5]https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html

Older people have a smaller reproduction number under the laissez-faire because of their reduced social interactions. The population-weighted reproduction number in the laissez-faire is thus $\overline{\Re}_0 = 2.48$, in line with the central scenario of the CDC. This is smaller than the often stated number $\Re = 3...5$ that has been estimated at the beginning of the pandemic. This reduction is made to account for the improved protective behavior coming from the understanding of the basic prevention efforts (no hand-shaking, mask bearing, ...) that have been observed more recently.

As in Acemoglu et al. (2020), I assume an efficiency rate of confinement of 75%, i.e., one confined person in four behaves without any lockdown constraint. I also assume that a proportion of 50% of confined people are able to telework, whereas the others are totally unable to generate any economic activity. This is in line with the estimation of a 5.8% of GDP loss in France during the first quarter of 2020.[6] I assume an economic loss of a full confinement by a middle-aged person equaling $1/N_m$. This means that a 100% confinement of the middle-aged people without any telework capability during one year would generate a 100% GDP loss. In this calibration, telework halves this loss. I also assume that confining a young or a senior person yields no economic loss. This is in line with the fact that GDP does not take account of most contributions of these two age classes to the wealth of the nation.

The health care capacity is France is 6 hospital beds per 1,000 inhabitants. I assume that half of this capacity can be mobilized for the pandemic, so that $\overline{h} = 0.3$. The hospitalization rate among infected people is assumed to be 0.1%, 2% and 12%, respectively for the young, middle-aged and senior class. This has been estimated for France in mid-April 2020 by Salje et al. (2020). This study has also produced the following statistics about mortality rates: π_{0j} equals 0.001%, 0.15% and 3.65% respectively for $j \in \{y, m, s\}$. These mortality rates of covid are multiplied by a factor 5 if the hospital capacity is overwhelmed. There is no credible data to support this assumption, which is used to justify the classical "flattening the curve" policy.

It remains to calibrate the value of lives. I discuss this critical issue in Gollier (2020), remarking in particular that the absence of any democratic debate on this issue over the last five decades during which Western governments used a "value of statistical life" for policy evaluation is problematic. In this paper, I value a life lost at 60, 40 and 20 annual GDP/cap, respectively for the young, middle-aged and senior classes.[7] For example, if one percent of the population dies, all aged 65 years or more, this has the same effect on welfare than a 20% reduction in annual GDP. This is equivalent to 60% if the 1% death toll is borne by the young generation. Robinson, Raich, Hammitt and O'Keeffe (2019) have surveyed studies using differentiated values of life for children compared to adult. They conclude that "the ratio of values for children to values for adults ranges from 0.6 to 2.9; however, most estimates are greater than 1.5." My benchmark calibration reflects this meta-observation. Balmford, Bateman, Bolt, Day and Ferrini (2019) used a contingent valuation method to estimate the value ratio of child to adult, with a value of 2.37 in the baseline case. This is also in line with my calibration. This benchmark calibration is summarized in Table 2.

Finally, I assume that no policy is implemented during the first 3 weeks of the pandemic.

[6] https://www.insee.fr/fr/statistiques/4485632

[7] Greenstone and Nigam (2020) have a similar age-dependent valuation system.

	Value	Description
γ	1/18	Daily recovery rate
β_q	0	Daily contagion rate of quarantined persons
β_c	0.1	Daily contagion rate of confined persons
β_f	0.6	Daily contagion rate of working persons
κ	0.35	Proportion of asymptomatic positives
θ	0.75	Efficiency rate of confinement
ξ	0.5	Proportion of telework
T_{vac}	1.5×365	Days before mass vaccination
I_{min}	0.05	Extinction threshold of the pandemic (in %)
$\overline{h}$	0.3	Hospital capacity (in %)
N	(22.7, 56.8, 20.5)	Distribution of population (in %)
π_0	(0.001, 0.15, 3.65)	Normal mortality rate (in %)
π_1	$5\pi_0$	Crisis mortality rate (in %)
h	(0.1, 2.0, 12.0)	Hospitalization rate (in %)
ϵ	(1, 1, 1)	Initial fraction of infection (in %)
w	(0, 176, 0)	Economic loss of confinement (in % of GDP/cap)
ℓ	(60, 40, 20)	Value of life lost (in years of GDP/cap)
$\alpha_{1.}$	(2, 0.5, 0.25)	Intensity of transmission from young
$\alpha_{2.}$	(0.5, 1, 0.25)	Intensity of transmission from adult
$\alpha_{3.}$	(0.25, 0.25, 0.5)	Intensity of transmission from senior
p	7	cost of mass PCR testing (in % of GDP/cap)

Table 2: Benchmark calibration of the MR-SIR model.

b	$\overline{\Re}_{22}$	t^*	$\overline{R}_{t^*}$	D_y	D_m	D_s	W	L
0.0	2.05	220	84.0	0.001	0.32	1.74	3.73	51.42
0.1	1.78	237	79.5	0.001	0.28	1.43	4.33	44.26
0.2	1.53	260	73.3	0.001	0.22	1.02	5.37	34.67
0.3	1.29	291	64.9	0.000	0.06	0.27	7.13	15.05
0.4	1.08	328	52.7	0.000	0.05	0.20	10.87	16.91
0.5	0.88	349	37.9	0.000	0.04	0.13	16.13	20.25
0.6	0.71	304	24.8	0.000	0.02	0.08	18.82	21.44
0.7	0.55	228	17.1	0.000	0.02	0.06	17.29	19.08
0.8	0.41	176	13.2	0.000	0.01	0.05	15.35	16.75
0.9	0.29	146	11.1	0.000	0.01	0.04	14.20	15.39
1.0	0.19	127	9.9	0.000	0.01	0.03	13.53	14.61

Table 3: Outcome of the uniform confinement policy as a function of the strength b of the confinement. $\overline{\Re}_{22}$ is the reproduction number at the beginning of the confinement period (22^d day of the pandemic). t^* is the duration of the pandemic (in days), and $\overline{R}_{t^*}$ is the overall immunity rate (in %) at that date. D_j is the share of population who dies in age class j (in % of whole population). W and L are respectively the economic loss and the total loss (in % of annual GDP).

4 Constant uniform confinement policies

In this section, I explore different no-test confinement policies in which the intensity of the confinement is uniform in the population. The simplest version of this family of lockdown strategies takes the form of imposing a uniform strength b of confinement until the threshold prevalence rate I_{min} is attained to obliterate the virus in the population. The outcome of such policies is described in Table 3 for different lockdown intensities $b \in [0, 0.9]$.

Let me start with the laissez-faire policy ($b = 0$), whose outcome is described by the first line in Table 3 and by Figure 2. Only the symptomatic persons are quarantined under this policy. At the 22^d day of the pandemic, the reproduction number is down to $\overline{\Re}_{22} = 2.05$, because the share of susceptible persons has already been reduced to 92%. After two months of the pandemic, the wave of infection peaks, in which more than one-fourth of the young and middle-aged people are simultaneously sick. Because seniors have intrinsically less social contacts, they are much less infected. Because of this huge wave of infection, hospitals remain overcrowded during almost three months, implying a catastrophic death toll in which 8.5% and 0.6% of respectively the senior and the middle-aged people die. It takes 220 days for the pandemic to die out thanks to the herd immunity. At that time, respectively 94%, 92% and 53% of the young, middle-aged and senior people are immunized, meaning herd immunity is obtained with an immunization rate of 84%. The economic loss amounts to as little as 3.73% of annual GDP, due to the revenue loss of quarantined and deceased people during the period. But when valuing the lives lost, the total loss equals a dismal 51% of annual GDP.

This laissez-faire policy illustrates the necessity of "flattening the curve" with the objective to preserve some bed capacity in hospitals. This is done by imposing some lockdown in the economy. However, doing so implies additional costs due to the confinement itself, but also to the increased time to eradicate the virus. Let me illustrate this in Figure 3 with the policy in which a $b = 30\%$ confinement is imposed after 3 weeks of laissez-faire. It now takes 291 days to eradicate the virus. Because social interactions are reduced, herd immunity is now obtained with a 65% immunization rate.[8] Combining this with the fact that hospitals are not overcrowded implies that the rates of mortality is reduced to 1.3% for senior people and to 0.1% for the middle-aged people. The economic cost goes up to 7.13% of annual GDP due to the lockdown, but the total cost of the pandemic is now limited to 15.0% of annual GDP.

Should we go farther in the intensity of the lockdown once we have have flatten the curve enough to escape hospital overcrowding? The public planner faces here a dilemma. Strengthening the lockdown increases the economic cost due to the reduced labour and the increased duration of the lockdown. But it reduces the death toll. However, this marginal benefit is much reduced because the mortality rate is now much less sensitive to b due to the fact that the bed capacity constrained is slack. As a consequence, for $b \in [0.29, 0.57]$, the marginal economic cost of increasing the intensity of confinement is larger than its marginal benefit in terms of reduced lives lost.

There is a limit to this argument. A very strict confinement is able to suppress the virus in a short period of time. When the confinement intensity is larger than 57%, the sensitivity of the pandemic duration to the severity of the confinement is so large that any marginal increase in confinement *reduces* the economic cost of the policy. This is probably due to the fact that the reproduction number is a quadratic function of b, whereas the economic cost is linear in b. Because increasing b also reduces the death toll, the total cost of the policy is decreasing in the strength of the confinement for large b. Consider for example the case case of a confinement intensity of $b = 90\%$, as illustrated in Figure 4. With such a strong confinement, the reproduction number goes down to $\overline{\Re}_{22} = 0.29$ on the day the confinement is implemented. This implies a fast reduction in the prevalence rate. The pandemic is terminated within 146 days, with a rate of immunity that is limited to 11.1% at that time. The economic loss is relatively large, but the global mortality rate is reduced to 0.05% of the whole population. This yields a total loss of 15.39%, similar to the total loss associated with the much milder confinement rate $b = 30\%$.

To sum up, one can consider two possible uniform confinement strategies, corresponding to two local minima for total cost in Figure 9. One can go for a "flatten-the-curve" strategy, or for a "suppression" strategy. The flatten-the-curve strategy is supported by a limited confinement intensity that is just large enough to escape hospital overcrowding. But it requires a large fraction of the population to be infected and to recover in order to build herd immunity. The suppression strategy is implemented with a very high confinement intensity to obliterate the virus in the population at the fastest possible speed. There is a set of bad policies between these two strategies in which economic costs and the mortality rate are larger. Hesitating between the flatten-the-curve strategy and the suppression strategy can be very costly. The current relatively high tolerance to breaking the strong confinement rules in some countries could bring us in this dismal outcome, with a longer duration of the pandemic, more lives lost, and larger economic losses. This is the curse of the hesitant confinement. Another illustration of the necessity of maintaining a time-consistent policy is documented in Figure 1

[8] Observe that the timing of the termination strategy is crucial here. I assume that the testing-and-tracing search for the 0.01% remaining contagious people in the population at day $t^* = 291$ can be quarantined before exiting from the lockdown.

when the planner abandon the suppression strategy too early to switch to a flatten-the-curve strategy.

In this section, I examined constant strategies. This may not be optimal. For example, when crushing the curve of infection, actual policies around the world have tended to impose a strict confinement strategy at the beginning of the policy period to relax it once the rate of prevalence is considered to be low enough. Could this kind of time-varying strategy generates a better outcome compared to constant strategies? To answer this question, let me start with suppression strategies. Observe that under these strategies, the rate of change in the number of susceptible persons in each age class is almost zero for most of the strict confinement policy, as seen in Figure 4. In that case, the dynamic of the pandemic simplifies to

$$I_{i,t+1} - I_{i,t} = \left(\sum_{j=1}^{J} \hat{\beta}_{ijt} I_{j,t} \right) - \gamma_i I_{i,t}, \tag{12}$$

with $\hat{\beta}_{ijt} = \beta_{ijt} S_i$. In that case, as observed by Pollinger (2020), the dynamic of infection is purely exponential, with $I_{t+1} = A(x_t) I_t$ where I_t is the vector of age-specific numbers of infection, and $A(x_t)$ is a 3x3 matrix that is a time-independent function of the policy variables $x_t = (a_{.t}, b_{.t})$. In that case, we obtain the following result.

Proposition 1. *Consider the set of suppression strategies in which the rate of change in the number of susceptible persons is almost zero. In this set, the cost-minimizing strategy is characterized by almost constant age-specific intensities of confinement and testing.*

Proof: In this proof, I denotes a 3x1 vector of age-specific numbers of infection, and x is a vector of policy variables that affect the 3x3 infection matrix $A(x)$ together with the convex per-period cost $w(x)$ of the policy. Consider all policies which imply the same age-specific rates of prevalence I_T at some date $T > 0$. I look for the dynamic strategy $(x_1, ..., x_T)$ which is feasible in the sense that the rate of infection at date T is I_T and that minimizes the cumulated economic cost:

$$\min_{x_1,\dots,x_T} \quad \sum_{t=1}^{T} w(x_t) \quad \text{s.t.} \quad \left(\prod_{t=1}^{T} A(x_t) \right) I_0 = I_T. \tag{13}$$

Let A be the solution of the equation $A^T I_0 = I_{min}$. Obviously, the solution of the following static problem

$$x^* = \arg\min_x \quad w(x) \quad \text{s.t.} \quad A(x) = A \tag{14}$$

characterizes the optimal solution $(x_1, ..., x_T) = (x^*, ..., x^*)$ of the dynamic problem (14). ∎

This means that, at least for strategies aimed at crushing the curve of infection, limiting the search of policies to constant confinement and testing policies, potentially age-specific, is not restrictive. Of course, this result cannot be generalized to strategies aimed at flattening the curve in which the susceptible numbers S_{it} vary widely over time, so that matrix A is not a time-independent function of the policy. Also, when considering an objective that combines the economic loss and the value of lives lost, it may be optimal to start with a stricter confinement rule that can be relaxed over time. However, because under our calibration the total loss is mostly entirely concentrated in the economic cost of the confinement, this effect of lives lost is expected to be marginal. The optimal crush-the-curve policy yields an almost constant confinement effort all along the duration of the pandemic. Proposition 1 can be interpreted as a special case of the model by Pollinger (2020) extended to MR-SIR. Pollinger characterizes the dynamic confinement strategy that minimizes total cost in the standard SIR model when the rate of change of S_t is almost zero. In his model, the dynamics of infection is such that $\partial I_t/\partial t = a(x)I_t - X(I_t)$, where $X(I)$ is an exogenous extraction technology from the pool of infected people. In my model, X equals zero everywhere except at $I = I_{min}$ where $X(I)$ equals I. The more comprehensive objective function and the richer set of extraction technologies considered by Pollinger yield much broader properties of the optimal solution. Under a weak condition on the extraction function X, Pollinger shows that the optimal intensity of confinement is decreasing with time.

5 Time-variable uniform confinement policies

I also examine non-discriminating confinement strategies that fluctuate over time. The lack of understanding of the dynamics of the pandemic and the difficulty to behave responsibly by a fraction of the population puts a strong pressure on the political system to exit from lockdown, or at least to relax the constraints, when the hospitalization rate goes down. I therefore explore the welfare impacts of "stop-and-go" strategies defined by four parameters: $\overline{b} \geq \underline{b}$ and $\overline{I} \geq \underline{I}$. After 3 weeks of an unconstrained circulation of the virus in the population, one starts with implementing a high confinement $\overline{b}$. As long as the prevalence rate I_t is larger than a minimum threshold $\underline{I}$, this strict rate of confinement is maintained. Once this threshold is attained, the lockdown is exited and a lower rate of confinement $\underline{b} \leq \overline{b}$ is imposed. It is maintained as long as the prevalence rate remains lower than $\overline{I}$. Once this threshold is attained, the larger confinement rate $\overline{b}$ is reimposed, and so on until the prevalence rate attains I_{min} to obliterate the virus. Notice that uniform policies are special cases of stop-and-go policies in which $\underline{b}$ and $\overline{b}$ are the same.

In this section, I fix the trigger points $(\underline{I}, \overline{I})$ at respectively 20% and 80% of the bed capacity in the country. This guarantees that hospitals are never overcrowded. It also allows for reducing the intensity of the lockdown when a strict lockdown is unnecessary to flatten the curve.

Consider for example the stop-and-go policy with $\underline{b} = 0.2$ and $\overline{b} = 0.8$. Figure 6 describes the dynamic of the pandemic under this policy. It entails 3 waves of infection. After the first wave due to the laissez-faire of the first three weeks, a strict lockdown of 26 days is imposed that reduces the prevalence rate. Then, for 44 days, the intensity of the lockdown is weakened, which generates a second wave of the pandemic. This triggers a second strict lockdown that lasts for 26 days. Finally, the lockdown is weakened once again, which triggers a third wave. However, given the high rate of immunity prevailing in the population, no more strict lockdown need to be imposed because the hospitalization rate remains manageable. The pandemic lasts for 475 days. The economic loss is limited to 12.26%, and the mortality rate equals 0.1% and 1.2% respectively for the middle-aged and senior classes. The total loss is 19.36%.

In Table 4, I describe other stop-and-go strategies. For the sake of completeness, I added to this table the suppression policy $\underline{b} = \overline{b} = 0.9$ that I identified in the previous section as a

$\underline{b}$	$\overline{b}$	t^*	$\overline{R}_{t^*}$	D_y	D_m	D_s	W	L
0.2	0.8	475	59.7	0.000	0.06	0.24	12.26	19.36
0.4	0.6	473	43.4	0.000	0.04	0.16	18.55	23.36
0.3	0.9	360	60.9	0.000	0.06	0.25	10.83	18.10
0.5	0.9	451	30.2	0.000	0.03	0.10	23.75	26.98
0.9	0.9	146	11.1	0.000	0.01	0.04	14.20	15.39
0.0	0.3	386	68.4	0.000	0.06	0.30	5.74	14.28

Table 4: Outcome of the stop-and-go confinement policy as a function of the strict and weak strengths $(\underline{b}, \overline{b})$ of the confinement. Notation and units are as in Table 3.

potentially good suppression solution, yielding a total loss of 15.39% of annual GDP after a pandemic of 146 days. In terms of least-cost efficiency, it competes with the flatten-the-curve strategy consisting in maintaining a weak confinement $b = 30\%$ for 270 days. In Table 4, I examine another flatten-the-curve strategy in which that confinement intensity $\overline{b} = 0.3$ is maintained only during the period of time necessary to tip over the initial contagion wave. When the hospitalization rate goes back to 20% of bed capacity, a full relaxation of lockdown ($\underline{b} = 0$) is decided. This happens on day 165 of the pandemic, which dies out on day 386 without a second wave. It yields a record low total loss of 14.28% of annual GDP. This total cost is similar in level to the one described in the previous section, but it's composition is different, with a smaller economic cost and a larger mortality rate. This two-stage strategy looks similar to the optimal uniform strategy described by Acemoglu et al. (2020). They show that the optimal uniform strategy under their calibration imposes a confinement that peaks at 50% of the population for a short period of time at the beginning of the pandemic, then stabilizes at around 30% for several months, and finally goes to zero when the infection rate vanishes. Notice however that the duration of their 30% confinement is close to one year, whereas I predict that half a year would be enough.

Although the crush-the-curve and flatten-the-curve strategies documented by the last two lines in Table 4 yield similar total costs, the suppression strategy suffers from an important comparative weakness due to the low rate of immunity that prevails at the end of the pandemic. If only 11.1% of the population got immunity in a world where the virus continues to circulate in other regions, implementing the suppression strategy is possible only if frontiers remain sealed as long as the virus survives elsewhere. The associated cost of this closure of the frontiers are not counted in my model.

In Figure 7, I describe the total cost as a function of $(\underline{b}, \overline{b})$. The last two lines of Table 4 describe the two local minima of this bivariate function. This figure also illustrates the curse of hesitation between these two polar strategies of suppression and flatten-the-curve. A convex combination of these two policies if for example $(\underline{b}, \overline{b}) = (0.5, 0.9)$, which implies a total loss of 26.98% as described in Table 4.

Let me conclude this section on time-variable uniform confinement strategies with an analysis of the optimal flatten-the-curve strategy examined by Miclo, Spiro and Weibull (2020). These authors solve the problem of minimizing the economic cost of confinement in the standard SIR pandemic under a capacity constraint of the health care system. They show that it is optimal to impose no restriction as long as the capacity constraint is not

t^*	$\overline{R}_{t^*}$	D_y	D_m	D_s	W	L
288	78.0	0.000	0.07	0.38	4.43	14.90

Table 5: Outcome of the Miclo-Spiro-Weibull confinement policy of minimal daily confinement compatible with the health care capacity constraint, as described in Figure 9.

binding, and to impose the minimal degree of confinement compatible with the capacity constraint when it is binding. I describe the outcome and the dynamics of the pandemic under my benchmark calibration of the MR-SIR model in Table 5 and Figure 9. The virus circulates freely in the population for the first 34 days of the pandemic before the health care capacity constraint binds. Then, a 45% confinement is imposed, that goes down gradually for 66 days until the population is fully deconfined. The virus is eradicated after 288 days. The economic cost is minimal at 4.43% of annual GDP, but the total cost is evaluated at 14.90%. It is useful to compare this policy to the best constant flatten-the-curve strategy with $b = 30\%$ for 291 days, as described in Table 3 and Figure 3. Because the confinement is weaker and shorter in the Miclo-Spiro-Weibull strategy (they call it "filling-the-curve"), the economic cost is much smaller. But the rate of immunization is larger, in particular among the elderly whose immunity rate goes up to 49% (from 35%). Notice in particular that during the partial confinement period, the prevalence rate continues to grow in the senior class, which is compensated by a strong reduction of the prevalence rate in the other two age classes. This unfortunate dynamics implies an increase in the number of lives lost. In terms of total cost, the two strategies yield a similar outcome.

6 Age-specific policies

Up to now in this paper, I only considered policies that are non-discriminated across age classes. There are at least two reasons why one should consider confinement policies that are age-sensitive. First, the case-fatality rate is extraordinarily different at different ages. Therefore, it may be interesting to expose more less vulnerable people if, for example, herd immunity is the final outcome of the pandemic. This suggests that the intensity of the confinement should be made increasing with age. The second reason is that the economic cost of confinement is also very different across age classes. This suggests that middle-aged people should receive priority in the exit of the lockdown. Both reasons justifies a strong sheltering of the seniors. But these two reasons offer contradictory arguments for which of the young or middle-aged people should exit from the lockdown first. Adults are more valuable to send back to work, but they are more vulnerable to the virus.

Table 6 explores different possible age-specific policies. As a follow-up of the stop-and-go strategies considered in the previous section, I now assume two age-specific confinement intensities, $\underline{b} = (0, 0, 1)$ and $\overline{b} = (b_y, b_m, 1)$, that are triggered when the hospitalization rate passes through one of the two thresholds $(\underline{I}, \overline{I}) = (0.2\overline{h}, 0.8\overline{h})$. Seniors remain 100% confined until the end of the pandemic. After three weeks of the free circulation of the virus, the young and the middle aged people are confined with an intensity b_y and b_m, respectively. Both young and middle-aged people are fully deconfined when the hospitalization rate reach 20% of the bed capacity. Consider first the case in which the middle-aged class is fully

b_y	b_m	t^*	$\overline{R}_{t^*}$	D_y	D_m	D_s	W	L
1.00	0.00	401	68.6	0.000	0.08	0.13	3.01	8.58
0.80	0.00	368	68.1	0.000	0.07	0.13	3.00	8.52
0.25	0.10	256	70.8	0.000	0.07	0.13	3.62	9.11
0.00	0.18	250	71.3	0.000	0.07	0.13	4.16	9.59

Table 6: Outcomes of the age-specific confinement policy as a function of the young and middle-aged confinement strengths (b_y, b_m) of the confinement, assuming a 100% confinement of the seniors. Notation and units are as in Table 3.

deconfined, whereas 80% of the young class remain in lockdown for 115 days before exiting it. The dynamic of covid-19 in this case is described in Figure 9. The pandemic is eradicated after 368 days, so that the seniors remain under full confinement for one year under this policy. The confinement of the junior and senior classes flattens the curve enough so that hospitals are not overwhelmed. Because the working class is never confined, the economic cost is limited to 3% of annual GDP. All in all, the total cost of the pandemic is contained at 8.58% of annual GDP.

One may find sheltering the seniors for more than one year as socially, morally or psychologically unacceptable. An alternative solution would be to exit seniors at the same time as the young generation, after 115 days of lockdown. That would increase the mortality of the seniors from 0.13% to 0.19% of the entire population (46,000 additional deaths in the case of France), and it would increase the total cost from 8.52% to 9.91%.

If the objective is to flatten the hospitalization curve and at the same time to build herd immunity, it would be intuitive to do it by exiting the young first from the lockdown, since their hospitalization rate is 20 times smaller than the middle-aged, and their mortality rate is 150 times smaller. The tradeoff comes from the fact that it is more expensive to confine middle-aged people. Consider for example the bottom line of Table 6, which documents the pandemic dynamics when young are not lockdown, and 18% of middle-aged people are confined for 112 days. This is enough to protect hospitals from the covid wave, as shown in Figure 10. Because the same fraction of adults have been infected at the end of the pandemic, the two strategies yield the same global death toll. But because of the additional cost of confining some workers, the total cost of the adult confinement is larger than when the young generation is initially confined to flatten the curve.

In this study, I discriminate the deconfinement strategy only on the base of age. But we know now that comorbidities have a large impact on the mortality rate too. For example, in New York state, 86% of the 5,489 reported COVID-19 deaths before 6 April 2020 involved at least one comorbidity, according to the state's department of health.[9] Adding some of these comorbidities such as diabetes (37.3% of the New York deaths) and obesity in the individual characteristics of the discriminated deconfinement strategy could considerably reduce the death toll of age-specific strategies.

The main message of this section – together with all papers reviewed in the introduction dealing with this issue – is that there is a large social benefit of using an age-specific con-

[9]https://www.the-hospitalist.org/hospitalist/article/220457/coronavirus-updates/comorbidities-rule-new-yorks-covid-19-deaths

finement strategy to flatten the curve. Whether this should be organized through a large confinement of the young or a weak confinement of the middle-age is not key. What is key is the necessity to protect the seniors, in particular during the strong wave of contagion happening in the first semester of the pandemic. Building herd immunity by sending the young to school and the middle-aged to work would be a demonstration of intergenerational solidarity towards the elderly people (Gollier (2020)).

7 The economic value of mass testing

What is the value of the PCR test information in this framework? Suppose that it would require a person to be tested every week to detect his infection before becoming contagious. Let me estimate the unit cost of the test at 50 euros. This is a conservative estimation.[10] Thus, testing a person on a weekly frequency by using an efficient PCR test would yield an annual cost of 2600 euros, or approximately 7% of annual GDP/cap for the calibration on French data. Thus, I calibrate $p = 0.07$ to estimate the economic cost W of the policy, as defined by equation (8).

Suppose that the current policy is a brutal suppression strategy with a 100% confinement of the population until the virus is obliterated in the population. This will take 106 days for the policy to attain this objective, with a total cost of 14.61% of annual GDP. Suppose that a testing capacity is obtained that allows for testing a fraction a of the population every week. Consider a policy in which a fraction a of the apparently susceptible population is tested every week-end. Among these tested people, those who are tested negative go back to work for a week, and those who are tested positive are quarantined. The fraction $b = 1 - a$ of $\hat{S}_t$ which is not tested is confined for the week. Thus under this policy, only the tested negatives go back to work. Suppose that this policy is implemented until the virus is obliterated. Consider for example the case of a testing strategy a =50%. It will take 136 days to fight the pandemic under this policy. The total testing cost will equal 1.02%of GDP, whereas the confinement cost will amount to 7.56% of GDP, yielding a total cost of 9.70% when counting the value of lives lost. This total cost is reduced by one-third compared to the 100% confinement of the brutal confinement strategy. I describe the relationship between the testing intensity a and the total cost of the pandemic in Figure 11. If one could test the whole population every week, the pandemic could have been obliterated in 103 days, for a total cost of 2.80% of annual GDP.[11] This is the least-cost policy among the set of policies that I have examined in this paper. The bottom line of this comparative statics exercise is that developing a mass testing capacity could reduce the total cost of the suppression policy by a factor 5.

Developing a mass testing capacity is also useful to implement the flatten-the-curve strategy. Remember that the best uniform strategy to flatten the curve is to impose a stop-and-go confinement policy with $\underline{b} = 0\%$ and $\overline{b} = 30\%$, implying a total cost of 14.28% of annual GDP (see Table 4). This confinement intensity is just enough to suppress the risk of overwhelming the bed capacity in hospital. We can reproduce a similar dynamics by replacing the 30% uniform confinement by a 36% testing, with the same result to maintain the bed capacity

[10] This is the current price of covid PCR tests on the free market, which contains a mark-up. Increasing return to scale should also affect the cost negatively in the future.

[11] A mass testing experiment has been put in place in the city of Vò in Lombardy. Although the city was one of the most important covid cluster in March, the city is now considered free of the virus.

constraint slack. This test-only strategy reduces the total cost of the pandemic to 12.18% of annual GDP.

A similar exercise can be made to examine the age-discriminated flatten-the-curve strategy in which the confinement intensity equals 0%, 18% and 100% respectively for the young, the middle-aged and the senior class. As documented in Table 6, this yields a total cost of 9.59%. Consider an alternative strategy in which the young and the old generations continue to be respectively fully unlocked and fully sheltered. For the middle-aged people, suppose that 23% are tested and 77% go to work without testing. The total cost is reduced to 8.64%.

8 Sensitivity analysis

Given the high uncertainty that surrounds several parameters of the model, it is crucial to perform various robustness exercises. This work is summarized in Table 7. Different sets of rows document the effect of changing one parameter on three strategies: the suppression strategy $b = 0.9$; the strategy of uniform confinement that is just enough to flatten the curve given the health care capacity; and the best age-specific strategy that flattens the curve with a 100% confinement of the seniors and a partial confinement of the other two age classes. The first row summarizes the best policies with the set of parameters described in Table 2. Under this benchmark case, sheltering the seniors is the obvious winner, followed by the strategy of uniformly flattening the curve. The next row report the impact of uniformly doubling the value of life. This does not affect the structure of the policies under scrutiny, but it changes the weights in the objective function. Increasing the value of life makes more attractive policies that preserve more lives, i.e., suppression and sheltering the old. Suppression now clearly dominates flattening the curve under this alternative calibration. I also report on the impact of reducing the value of lives lost for the elderly, considering the fact that many covid fatalities have other co-morbidity factors and a relatively limited remaining life expectancy. Reducing the value of lives lost of people aged 65+ years to 10 GDP/cap has the effect to make the fatten-the-curve policy much more favorable.

I could have reported other robustness checks in which the relative values of lives lost across ages are altered compared to the benchmark. For example, a standard practice is to use a value of statistical life that is independent of age (US-EPA (2010), Greenstone and Nigam (2020)). Reducing the value of life of the young relative to the senior reinforces the recommendation to shelter the old generation under age-specific confinement strategies. In fact, there is no reasonable valuation system that could reverse this result. Gollier (2020) clarifies this point in a simple static analysis.

In the next row, I examine the impact of raising the rate of asymptomatic from 0.35 to 0.45. More asymptomatic cases implies more contagion since it reduces the number of infected people that are quarantined in the absence of test. This raises the mortality rate. If one follows the suppression policy, the economic cost also increases because of the increased duration of the pandemic. Under the flatten-the-curve strategy, the rate of confinement must be increased from $\bar{b} = 0.30$ to 0.51 in order to preserve hospitals. This also increases the economic cost. Under the old-sheltering strategy, the increased rate of asymptomatic cases forces the planner to confine all young people and 30% of the working age class.

In the benchmark calibration, one in four confined persons behaves as if not confined. In the next row, I increase this inefficiency of the lockdown to 2/4. Of course, this deteriorates

Parametrization	Policy	Duration (days)	Mortality (% of pop)	Econ cost (% of GDP)	Total cost (% of GDP)
Baseline	Crush curve	146	0.049	14.20	15.39
	Flatten curve	386	0.363	5.74	14.28
	Old sheltered	368	0.200	3.00	8.52
$\ell = (120, 80, 40)$	Crush curve	146	0.049	14.20	16.59
($\uparrow$ value life)	Flatten curve	386	0.363	5.74	22.82
	Old sheltered	368	0.200	3.00	14.03
$\ell = (60, 40, 10)$	Crush curve	146	0.049	14.20	15.01
($\downarrow$ value life)	Flatten curve	386	0.363	5.74	11.29
	Old sheltered	368	0.200	3.00	7.26
$\kappa = 0.45$	Crush curve	173	0.097	15.31	17.69
($\uparrow$ asympt.)	Flatten curve	433	0.429	6.92	16.91
	Old sheltered	366	0.236	4.54	10.76
$\theta = 0.5$	Crush curve	304	0.107	27.76	30.38
($\downarrow$ lockdown eff.)	Flatten curve	367	0.368	7.01	15.68
	Old sheltered	398	0.272	4.52	11.37
$\alpha_{3.} = (0.5, 0.5, 1)$	Crush curve	155	0.086	14.91	16.88
(s behaves as m)	Flatten curve	498	0.512	7.44	18.99
	Old sheltered	429	0.293	3.52	10.84
$\pi_{03} = 5.47\%$	Crush curve	146	0.068	14.20	15.78
($\uparrow$ s mortality)	Flatten curve	386	0.512	5.74	17.26
	Old sheltered	368	0.263	3.00	9.76
$w_y = w_s = 0.4$	Crush curve	146	0.049	16.72	17.92
(y, s create value)	Flatten curve	386	0.363	6.87	15.41
	Old sheltered	368	0.200	7.45	12.96

Table 7: Sensitivity analysis.

the attractiveness of the suppression strategy, in which all costs basically double. Because the uniform flattening of the curve relies less on confinement, it is much less affected by the increased lockdown inefficiency. In fact, the misbehavior observed in the population can be compensated by an increased intensity of confinement from $\bar{b} = 0.3$ to 0.43, thereby marginally increasing the economic cost of the pandemic. Concerning the strategy of sheltering the seniors, the reduced efficiency of the confinement also necessitates increasing the intensity of the lockdown for the younger generations. To escape hospital overcrowding, one needs to fully confine the young class, together with some people from the working age class. This has a sizeable impact on the total cost.

In the benchmark calibration, the intensity of social interactions goes down with age, as expressed by equation (10). Suppose alternatively that senior people behaves as the middle-aged class:

$$\alpha_{..} = \begin{pmatrix} 2 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{pmatrix} \tag{15}$$

Obviously, this is no good news, as this raises the reproduction numbers. If applying the suppression policy, the duration of the pandemic will be longer, and the mortality rate will be larger, in particular in the senior class. However, because the virus is contained in the early stage of the pandemic the global impact of these increased social interactions remains marginal. We cannot say the same thing when flattening the curve. Because senior people are more integrated in the population, they contribute much more to the building of herd immunity. This massively increases their mortality rate, which goes up to 2.2% of their age class. Notice that the increased contagion implies that the uniform confinement rate must be increased to $\bar{b} = 0.41$ to flatten the curve. This implies that flattening the curve is now dominated by the strategy of suppression. Notice also that this increased integration of the seniors makes it more difficult to shelter them under the third strategy.

Next, I examine the effect of a 50% increase in the mortality risk of the senior people. Because the three policies that I examine in this table are rather protective of the old generation, the effect of this increased mortality risk is relatively limited in the number of lives lost and economic terms. Finally, similarly, increasing the economic cost of confinement of the young and seniors generations from 0 to 0.4, i.e., approximately one-fourth of the economic cost of the middle-age confinement, does not change much the results.

Clearly, this sensitivity analysis shows that the recommendation to shelter the seniors during the peak of infection is robust to changes in the parameters of the MR-SIR model. On the contrary, this also shows that there is no clear winner between the crush-the-curve strategy and the flatten-the-curve strategy.

9 Concluding remarks

When only 1% of the population is infected, a strong confinement of the whole population is a rather inefficient way to fight the virus. To reduce the contagion by one person, one hundred persons are confined, yielding a large economic impact. Obviously, our ability to test people in order to deconfine the negatives would be a much better strategy.[12]

In the absence of a testing capacity, one possible strategy is to suppress the virus by a strong degree of confinement during a few months. In this context, increasing the strength of the confinement has a large effect on reducing the duration of the lockdown. It happens that the net effect of strengthening the confinement is to reduce the total cost of the pandemic. Therefore, if the objective is to suppress the virus as soon as possible, it makes no sense to reduce the confinement before the full eradication of the virus in the population. Because this strategy implies a very low rate of immunization until the end of the pandemic, stopping short of full eradication exposes the country to a restart almost from the beginning of the pandemic. Following this strategy thus requires a lot of time-consistency and a strong political resistance to the lobbies and to some increasingly impatient citizens.

Most SIR modelers explore an alternative strategy whose objective is to reach herd immunity in a relatively long horizon. Reaching herd immunity without controlling the speed of the pandemic exposes hospitals to a tsunami of infections, implying a terrible death toll.

[12] If our PCR test capacity is limited, Gollier and Gossner (2020) suggested to use a standard testing protocol in which several individual samples are pooled and tested with a single test. If the objective is to maximize the number of people to unlock, the optimal group size is approximately equal to the inverse of the rate of prevalence.

This is why reaching herd immunity may be an efficient strategy only if the infection curve is flattened via a weak confinement at the beginning of the immunization process. The economic impact of the policy is small, but the mortality is severe. Depending upon how Society value lives lost, this strategy can dominate the suppression strategy.

When implementing a non-discriminatory confinement policy, the senior class bears most of the burden of deaths, in spite of the lower intensity of their social interactions. This is because of the extremely large case-fatality proportion faced by people aged 70 and older. An efficient intergenerational solidarity would be to ask the younger generations to build Society's herd immunity by living their life, participate to the economy, get infected and recover from covid-19. More vulnerable people should be sheltered during this high-contagion period of the pandemic. This sheltering of the vulnerable increases the mortality of the young and of the middle-aged. This is the price they could pay to express their solidarity to the elderly. The mortality risk differential is so big that targeting herd immunity, flattening the curve and sheltering the old generation is a no brainer, with a total cost far smaller than any uniform policy. Confine a fraction of the young to flatten the curve, get the working age class back to work to reduce the economic cost, and shelter the senior class to reduce the death toll. Acemoglu et al. (2020) make a very similar final recommendation.

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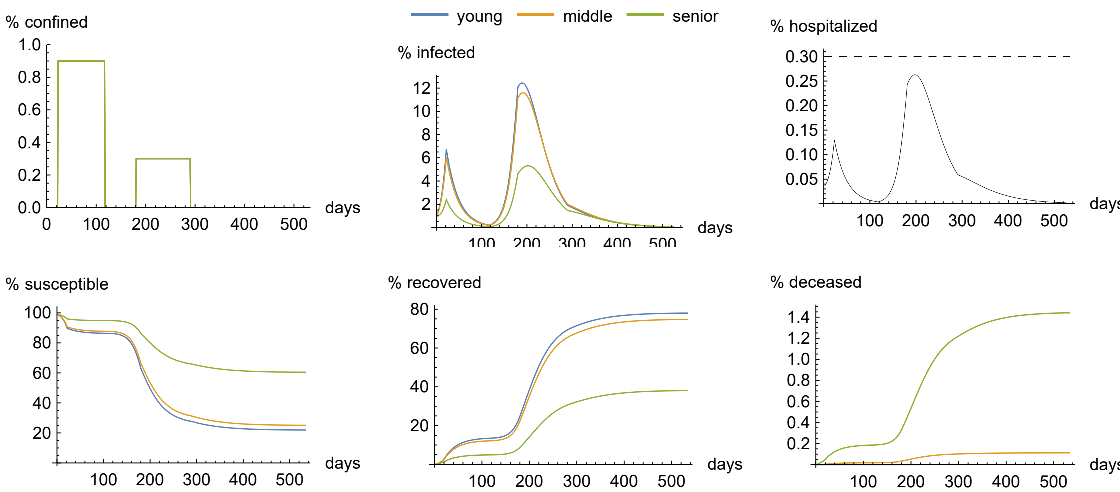

Figure 1: Dynamics of the pandemic when following the following strategy. After 21 days of free circulation of the virus, 90% of the population is confined for 95 days. Rather than maintaining this strong confinement until day 125 where the virus is fully eradicated, one shifts to the best flatten-the curve strategy one month short of this duration. Under this new flatten-the-curve strategy, a weak 30% confinement is established as soon as soon as the bed occupancy in hospital attains 80% of capacity during the second wave. Full exit to lockdown is decided when this occupancy rate goes below 20%.

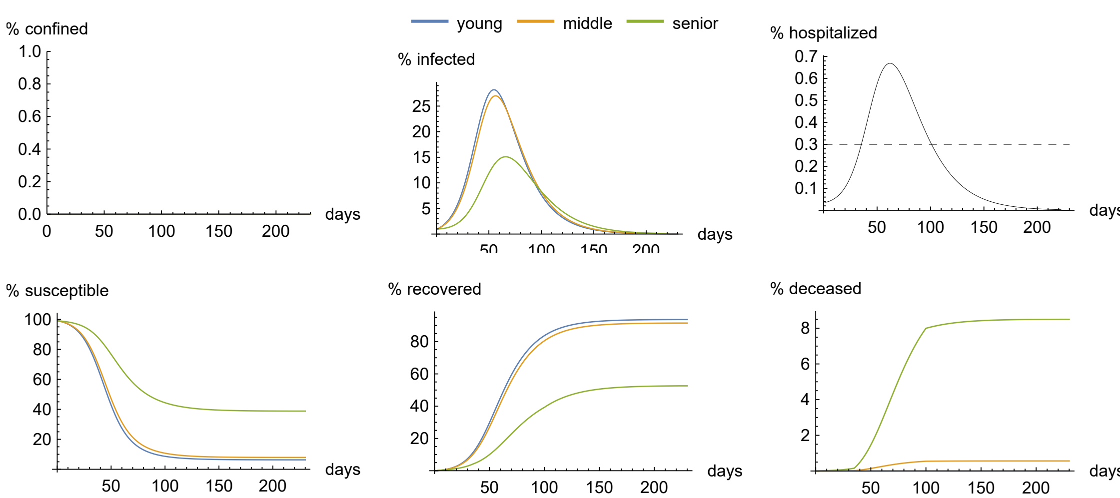

Figure 2: Dynamics of the pandemic in the laissez-faire strategy ($b = 0$).

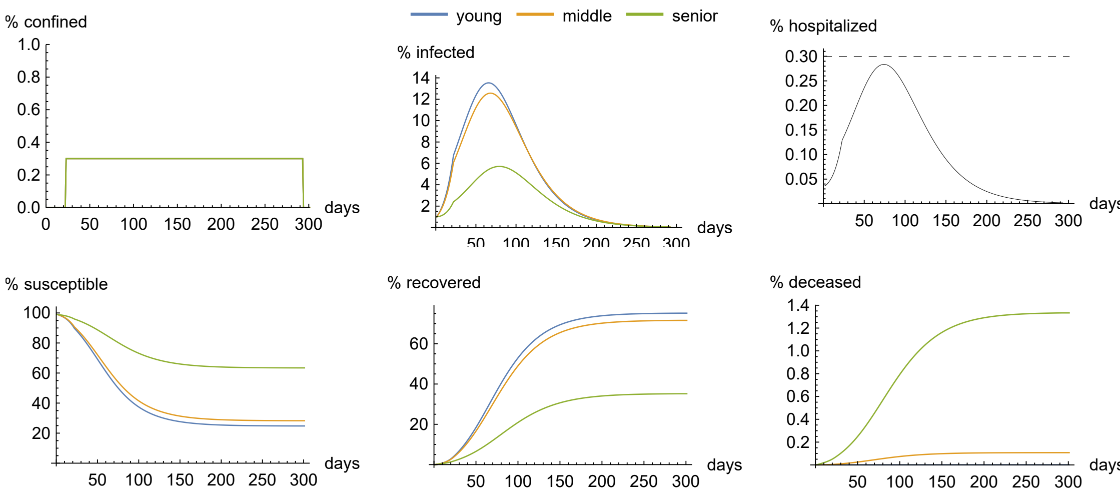

Figure 3: "Flatten the curve" strategy: Dynamics of the pandemic with a $b = 30\%$ lockdown after 3 weeks of laissez-faire.

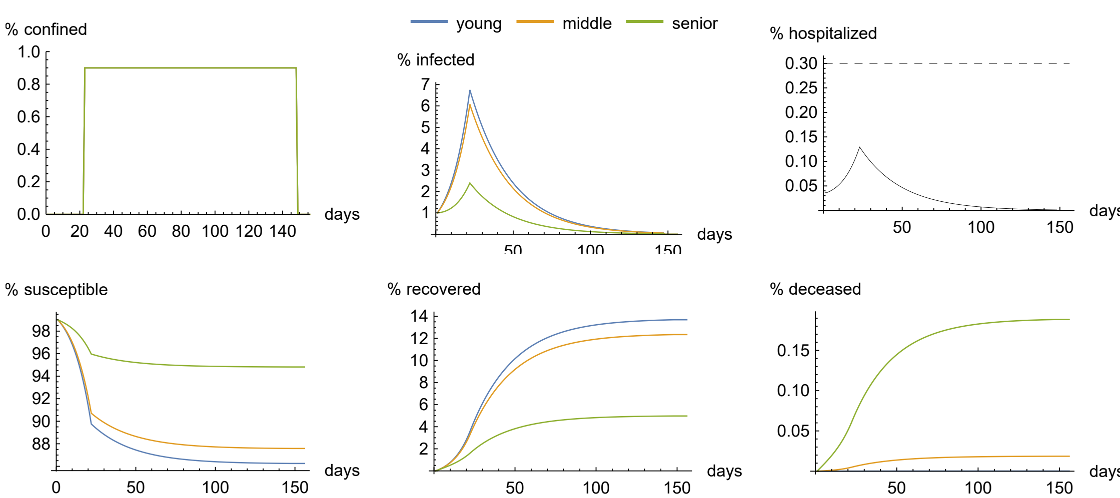

Figure 4: "Crush the curve" strategy: Dynamics of the pandemic with a $b = 90\%$ lockdown after 3 weeks of laissez-faire.

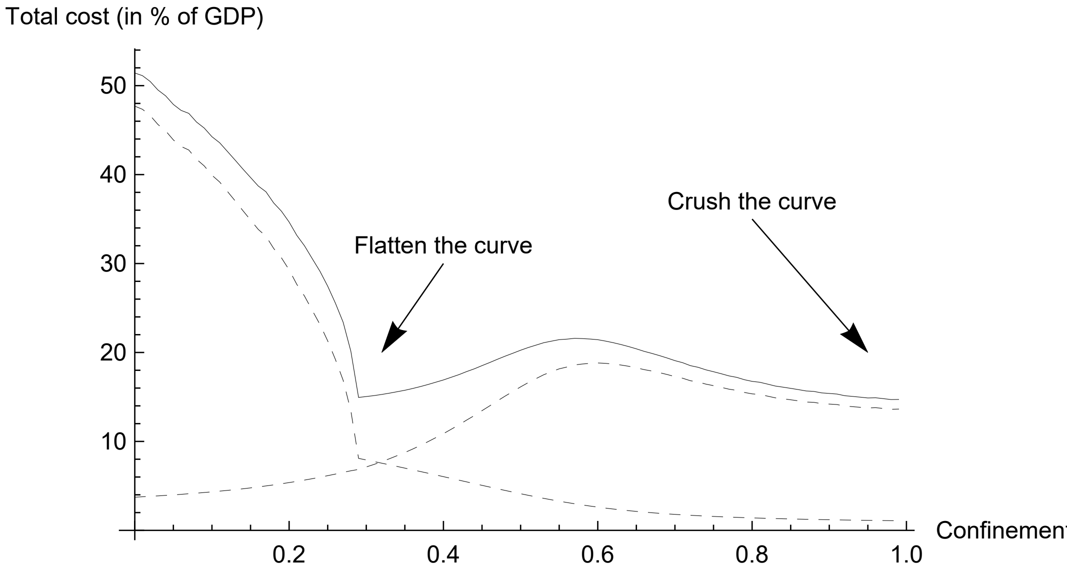

Figure 5: Total cost as a function of the uniform intensity of confinement. The dashed curves correspond respectively to the economic cost (hump-shaped) and to the value of lives lost (decreasing).

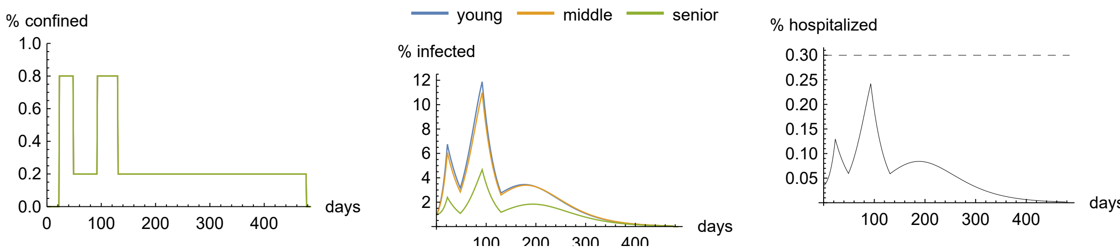

Figure 6: "Stop-and-go" strategy: Dynamics of the pandemic with $\underline{b} = 20\%$ and $\overline{b} = 80\%$. I assume the trigger points $\underline{I} = 0.2\overline{h}$ and $\overline{I} = 0.8\overline{h}$.

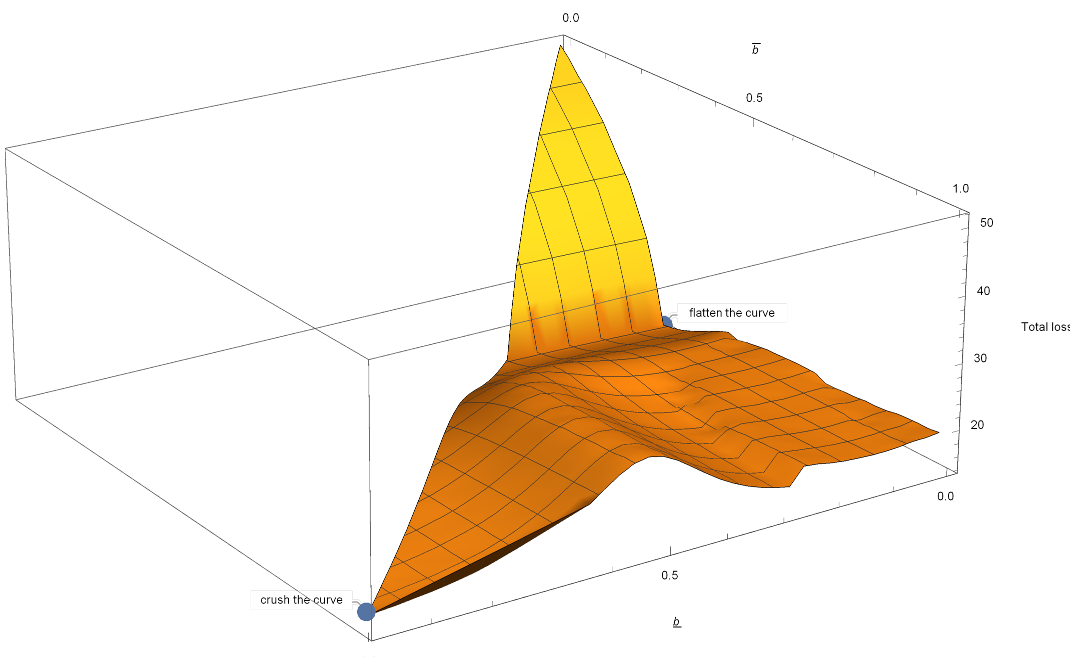

Figure 7: Total loss in stop-and-go strategies as a function of $(\underline{b}, \overline{b})$. I assume in this section the trigger points $\underline{I} = 0.2\overline{h}$ and $\overline{I} = 0.8\overline{h}$.

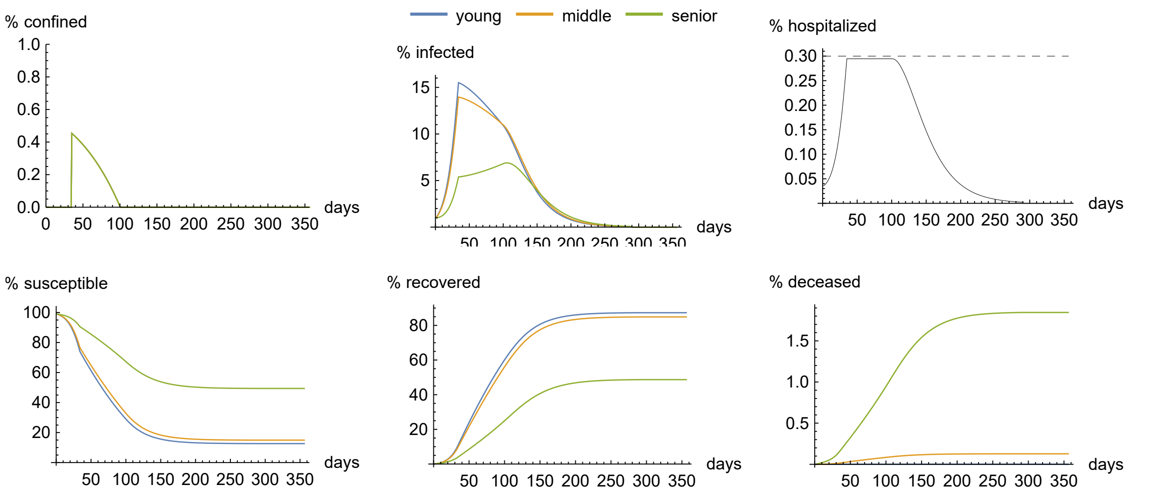

Figure 8: Optimal flatten-the-curve strategy: Dynamics of the pandemic under the Miclo-Spiro-Weibull strategy of minimal daily confinement compatible with the health care capacity constraint.

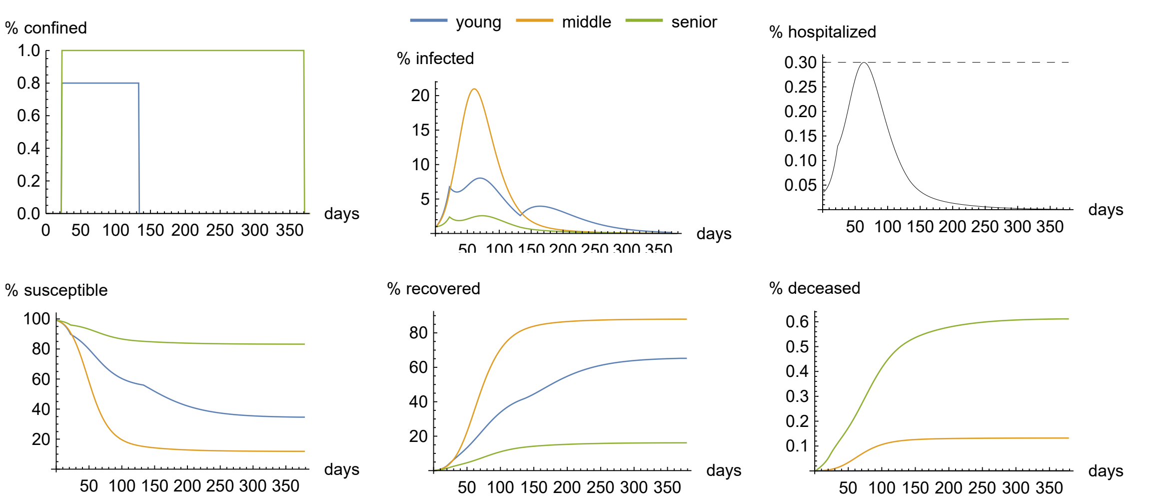

Figure 9: Age-specific policy with young confinement: Dynamics of the pandemic with $b_y =$ 80% and $b_m = 0\%$. Seniors are 100% sheltered.

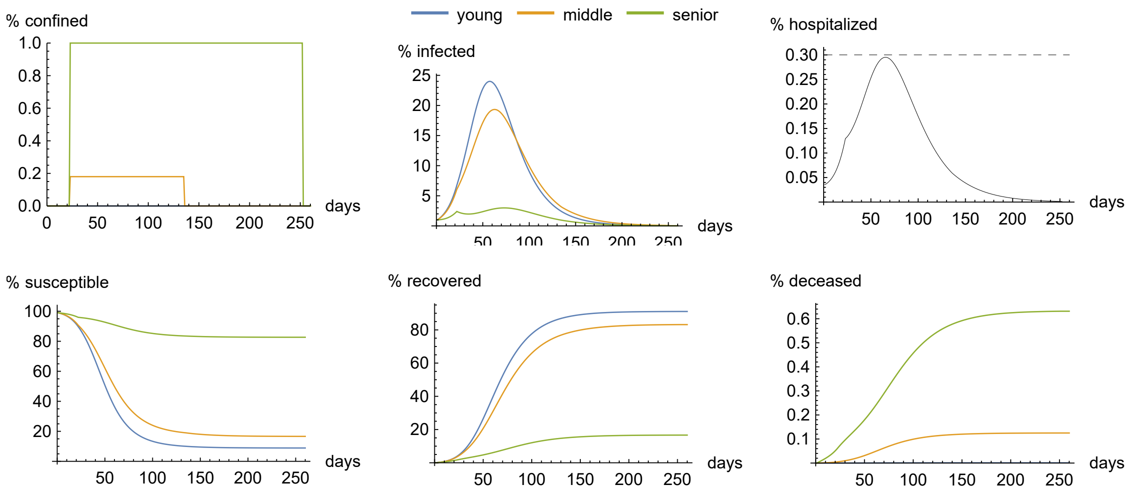

Figure 10: Age-specific policy with middle-aged confinement: Dynamics of the pandemic with $b_y = 0\%$ and $b_m = 0.18\%$. Seniors are 100% sheltered.

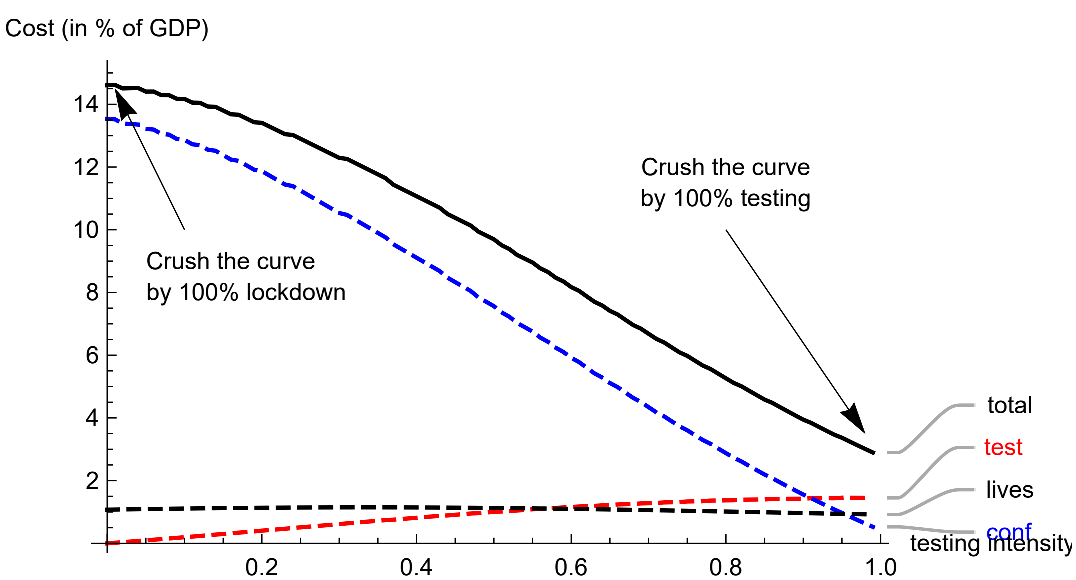

Figure 11: Value of testing when the susceptible population is either tested or confined on a weekly basis ($b = 1 - a$). The total cost and the costs of testing, confinement and lives lost are measured in percents of annual GDP, as a function of the testing intensity a.