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Abstract

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JEL Classification: D42, D62, H10, I18, L10

Keywords: Pandemics, Quarantine, SEIR-model, COVID-19

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Assessing the Consequences of Quarantines During a Pandemic*

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April 2020

Abstract

This paper analyzes the epidemiological and economic effects of quarantines. We use a basic epidemiologic model, a SEIR-model, that is calibrated to roughly resemble the COVID-19 pandemic, and we assume that individuals that become infected or are isolated on average lose a share of their productivity. An early quarantine will essentially postpone but not alter the course of the infection at a cost that increases in the duration and the extent of the quarantine. A quarantine starting at a later stage of the pandemic reduces the number of infected persons and economic losses, but generates a higher peak level of infectious people. A longer quarantine dampens the peak of the pandemic and reduces deaths, but implies higher economic losses. Both the peak share of infectious individuals and economic losses are U-shaped in relation to the share of the population in quarantine. A quarantine covering a moderate share of the population leads to a lower peak, fewer deaths and lower economic costs, but it implies that the peak of the pandemic occurs earlier.

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1 Introduction

This paper analyzes the epidemiological and economic effects of quarantines. More specifically, our focus is on how the timing, duration and extent of a quarantine impact on the dynamics of a pandemic as well as on economic losses.

In the absence of a vaccine or efficient drugs, countries have to adopt old-fashioned practices to combat the COVID-19 pandemic. One such policy is the use of quarantines, which slow down the spread of the infection. This means that fewer individuals will be infected at the peak of the infection and that the peak will occur later in time. Both these effects are important in order to prevent the health care system from being completely overwhelmed. However, quarantines

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have substantial economic costs, as production closes down when workers are confined to stay at home.

Countries have adopted very different strategies when it comes to the use of quarantines. China implemented an almost complete quarantine or lockdown in Wuhan and in some other cities in the Hubei province on 23 January. On April 8 the lockdown officially ended. Many European countries have also been using quarantines of various degrees of restrictiveness. For instance, Italy that has been hit very hard by the COVID-19 infection has implemented a very restrictive quarantine. In the most affected town of Codogno (pop. 16,000), police cars blocked roads into and out of the quarantined area and erected barriers. In Switzerland schools and most shops were closed nationwide, and on 20 March all gatherings of more than five people in public spaces were banned. Denmark was among the first European countries to introduce lockdown measures, starting on 13 March; since mid-April a very slow and gradual reopening has been initiated. At the other end of the spectrum is Sweden that has not yet (end of April) imposed any quarantine, keeps schools open and still allows public gatherings of up to 50 people.

We will in this paper analyze the effects of quarantines of different extents and durations that are imposed at different points during a pandemic. We use a basic epidemiologic model, a SEIR-model, that is calibrated to roughly resemble the COVID-19 pandemic.[1] As in Atkeson (2020) we assume that individuals that become infected on average lose a share of their productivity, and that also quarantined individuals on average incur productivity losses. However, our qualitative results do not depend on the assumed values of productivity losses. Our main findings can be summarized as follows.

1) The implementation of an early quarantine will essentially postpone but not alter the course of the infection, at a cost that increases in the duration and the extent of the quarantine.

2) A later starting day reduces the total number of infected and dead individuals as well as the economic losses, but it generates a higher infectious peak level.

3) There is a trade-off between economic costs and health outcomes in terms of the duration of a quarantine. A longer quarantine either postpone the peak (if it is implemented relatively early) or dampens the peak and reduces deaths (if it starts at a later stage of the pandemic), but implies higher economic losses.

4) The peak level of infectious people as well as economic losses are U-shaped in relation to the extent of a quarantine (the share of the population in quarantine). A quarantine of moderate extent, covering around half the population, leads to a lower peak, fewer deaths and lower economic costs than a more complete lockdown. However, it implies that the peak of infectious people occurs earlier.

Several recent papers analyze the implications of the policy response in relation to the COVID-19 pandemic. Dewatripont et al. (2020) discuss how to best use testing. Hall et al. (2020) analyze the optimal trade-off between consumption losses and pandemic deaths. Jones et al. (2020) studies the interaction of private and public mitigation efforts. Other policy options are

[1] This type of epidemiological model was introduced by Kermack and McKendrick (1927).

discussed in Baldwin and Weder di Mauro (2020a) and Baldwin and Weder di Mauro (2020b). More closely related to us, a number of recent papers specifically analyze the consequences of isolation enforcement. Anderson et al. (2020) discuss how mitigation policies will affect the COVID-19 pandemic. Casares et al. (2020) calibrates a dynamic model for the Spanish economy. The study shows how isolation or quarantine slows down the speed of the contagion and reduces the number infected and dead. However, they do not consider the economic effects of quarantines. Piguillem et al. (2020) calibrate a SEIR- model to Italian data, and calculate the optimal path of a quarantine for different functional forms of the planner's utility function. Similarly Alvarez et al. (2020) and Gonzalez-Eiras and Niepelt (2020) employ optimal control theory to determine the optimal path of a quarantine that can be continuously varied. We do not calibrate our model to any particular country and do not use control theory to pin down an optimal path of isolation. Our purpose is instead to try to shed light on some of the underlying trade-offs between economic and health outcomes when a quarantine is implemented.

2 The Model

We employ a SEIR-model similar to Atkeson (2020). There are five categories of individuals: susceptible persons (S) who have never been exposed to the virus; exposed persons (E) who carry the virus, but are not yet infectious; infectious persons (I); recovered persons (R) who are no longer infectious and, possibly, have developed resistance to the virus; and deceased persons (D). A susceptible individual becomes infected by infectious individuals at the rate βI. Exposed persons become infectious at rate σ. Infectious persons recover at rate γ and die at rate δ. The dynamics of the SEIR-model can be summarized as follows:

$$
\begin{aligned}
\dot{S} &= -\beta SI, \\
\dot{E} &= \beta SI - \epsilon E, \\
\dot{I} &= \varepsilon E - \gamma I - \delta I, \\
\dot{R} &= \gamma I, \\
\dot{D} &= \delta I.
\end{aligned}
$$

For simplicity it will be assumed that S, E, I, R and D represent shares of the population, i.e. $S(t) + E(t) + I(t) + R(t) + D(t) = 1$ at any point in time t.

Most countries have responded to the present Corona pandemic by imposing different types of quarantines, covering large parts of the population. In the context of the present model a quarantine would cover a constant share q of susceptible, exposed, infectious and recovered individuals over a certain period. The quarantined population would thus consist of the shares S_Q, E_Q, I_Q and R_Q. For simplicity we assume that there is no transmission of the virus among the quarantined population, i.e. $S_Q(t)$ remains constant during the quarantine. In reality, the virus could be transmitted within quarantined families; allowing for a small rate of transmission among the quarantined population would not alter our analysis qualitatively. Quarantined exposed individuals become infectious at rate σ, and quarantined infectious individuals recover at rate γ and die at rate δ. The dynamics during the quarantine can thus be summarized as follows:

$$
\begin{aligned}
\dot{S} &= -\beta S I, \\
\dot{E} &= \beta S I - \sigma E, \\
\dot{I} &= \sigma E - \gamma I - \delta I, \\
\dot{R} &= \gamma I, \\
\dot{D} &= \delta I + \delta I_Q \\
\dot{S_Q} &= 0, \\
\dot{E_Q} &= -\sigma E_Q, \\
\dot{I_Q} &= \sigma E_Q - \gamma I_Q - \delta I_Q, \\
\dot{R_Q} &= \gamma I_Q.
\end{aligned}
$$

After the quarantine has been terminated, the quarantined individuals join their corresponding groups, e.g. E_Q is added to E. Here, we do not account for quarantines that are introduced and lifted in steps. In reality, a government can vary the extent of a quarantine and let smaller groups of people return to normal life. However, there are infinitely many possibilities for implementing a quarantine. To keep our analysis transparent we only consider quarantines that take place once for a certain duration and covering a constant share of the population.

To assess the implications of a quarantine we will focus on the following measures:

(i) The peak of the share of infected individuals I_{Peak}. From a public health perspective it is desirable to dampen the maximum number of infected persons.

(ii) The day $t(I_{Peak})$ when the peak of the share of infected individuals occurs. For the public health authorities a later day is preferable, because it allows hospitals to be better prepared.

(iii) The share of the population that will have been infected and survived one year after the start of the pandemic, which is measured by the share of recovered individuals on day 365 of the pandemic $R(365)$; the share of deceased persons is obviously proportional to that number. To keep the number of infected and hence, deceased individuals low is one important objective.

(iv) The economic output during one year Y, from day 0 to day 365. In the absence of the pandemic it is assumed that productivity is 1 per individual and day, i.e. normalized total output would be 366 for the entire population. It is assumed that the productivity of susceptible, exposed and recovered individuals is 1 if there is no quarantine, whereas those in quarantine will have an average productivity $b = 0.5$, reflecting the fact that some individuals, e.g. individuals employed as manual workers, may have close to zero productivity, whereas other professions or tasks are easier to perform from home. Likewise infectious persons either have no or only mild symptoms or are sick at home or need costly treatment in a hospital. Their average productivity is decreased by a factor a, here set to $a = 0.5$. The productivity parameters determine the economic impact of the quarantine, but they do not affect the dynamic properties of the model.

Normalized total output at any day t is given by

$$Y(t) = S(t) + E(t) + R(t) + aI(t) + b\left[S^Q(t) + E^Q(t) + R^Q(t) + aI^Q(t)\right].$$

To assess the economic consequence of the pandemic, $Y = \sum_{t=0}^{365} Y(t)$ will be measured. It is thus implicitly assumed that the pandemic only has short-term consequences in the sense that it only leads to lost output due to illness and, possibly, a quarantine. Long-term structural effects are therefore not accounted for. Once the pandemic is over, the economy reverts to the status quo ante.

3 Simulations

We do not intend to calibrate the infection dynamics to any particular country or case, but we do have the COVID-19 pandemic in mind, and we therefore chose parameter values that have been suggested for this infection. The average incubation period is 5 days, but it seems that you can spread the infection two days before that.[2] We therefore set $\sigma = \frac{1}{3}$. We also assume that it takes on average two weeks to recover, implying that $\gamma = 1/14$, and that 0.1% of infectious persons die, i.e. $\delta = 0.001/14$.[3] Finally, we have $\beta = 0.2$ in the base case, which reflects the speed of the spread of the pandemic without a quarantine.[4]

[2] See He et al. (2020).

[3] This relatively optimistic value for δ is consistent with the study by Bendavid et al. (2020). However, the choice of δ has virtually no effect on the infection dynamics.

[4] This value of β is used by Alvarez et al. (2020).

3.1 Base case: no quarantine

The base case scenario has no quarantine. With our parameter values the pandemic dynamics during the course of one year looks as follows:

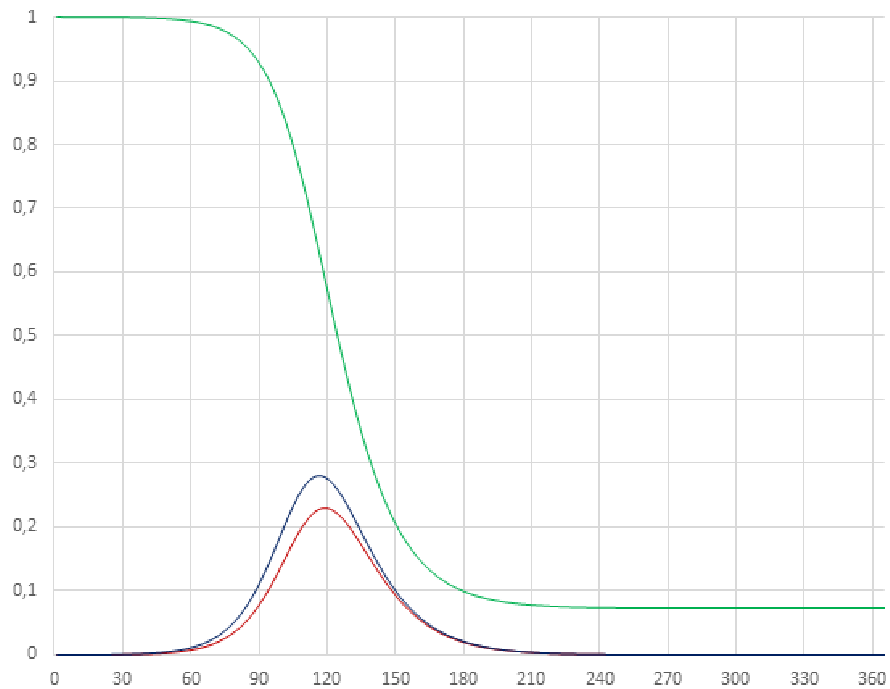

Figure 1. Pandemic dynamics in the absence of a quarantine

The horizontal axis measures days since the start of the pandemic, while the vertical axis measures shares of the population. The red curve represents the share of infectious individuals, the blue curve represents the share of infectious plus exposed individuals, and the green curve represents the share of infectious, exposed and susceptible individuals. That is, recovered and deceased individuals are represented by the area above the green curve; deceased people represent only a tiny fraction (0.1%) of these.

Assuming that at the start of the pandemic 0.01% had been exposed to the virus (i.e. $S(0) = 0.9999$), the peak of infectious individuals would occur on day 118 and represent 23 per cent of the population. Moreover, a year after the pandemic started almost 93% would belong to the category of recovered (and possibly resistant) individuals, implying a share of 7% still being susceptible.

Furthermore, assuming that the average productivity of infectious individuals is given by $a = 0.5$, output would be reduced from 366 to 359.28, i.e. a fall of 1.84%, due to the pandemic.

3.2 Introducing a quarantine

When assessing the effects of a quarantine several factors are of interest:

(i) timing, i.e. the start of the quarantine;

(ii) the duration of the quarantine;

(iii) the extent of the quarantine, i.e. how large a share of the population is covered.

We simulate below the importance of these factors using the same parameter values as above, and assuming an average productivity of quarantined persons given by $b = 0.5$.

3.2.1 Timing of the quarantine

The following figure illustrates the pandemic dynamics in the absence of a quarantine (solid curves, the same as in figure 1) and for a thirty-day quarantine covering 80 per cent of the population starting on day 30 of the pandemic (dashed curves). At early stages of the pandemic the starting date of the quarantine has almost no effect on the dynamics; a later starting date will simply postpone the pandemic.

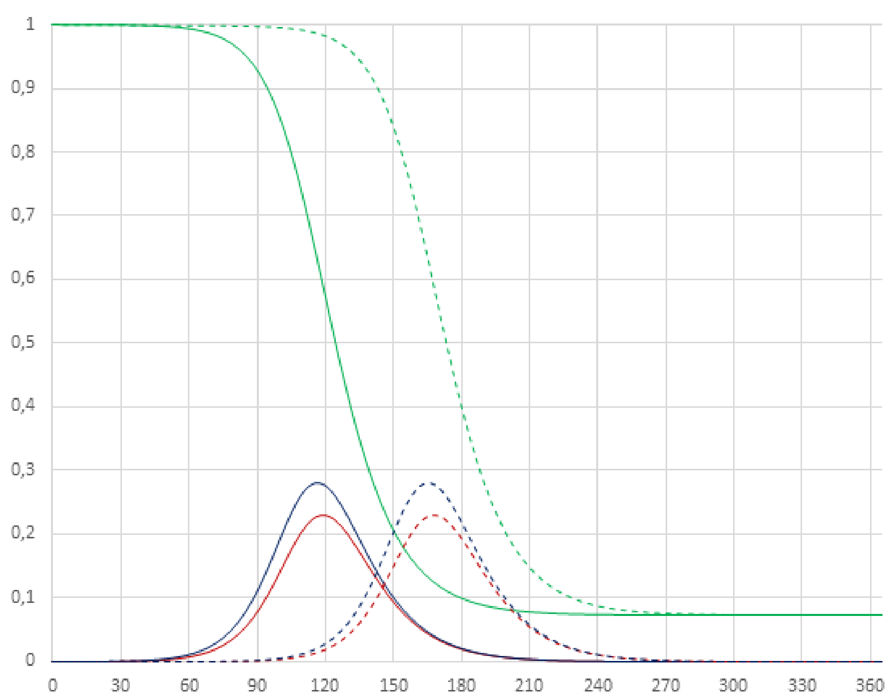

Figure 2. Pandemic dynamics with no quarantine and with a 30 day quarantine covering 80 per cent of the population starting on day 30

If the quarantine starts at a stage when the share of infectious individuals is increasing rapidly, the pandemic dynamics are affected differently, as illustrated by a quarantine starting on day 90 in the following figure (dashed-dotted curves). In this case there will be a double-peak in the share of infectious individuals, as its rise is stopped, but it starts increasing again after the quarantine has been terminated.[5] In case the quarantine starts later, just before or after the peak of the share of infectious individuals has been reached, there will be a faster drop from the peak (see the dotted curves in the following figure). Both cases leads to fewer infected compared to the base case, and therefore to fewer deaths. The later quarantine leads to fewer being infected, but at the cost of a higher peak level of infectious individuals.

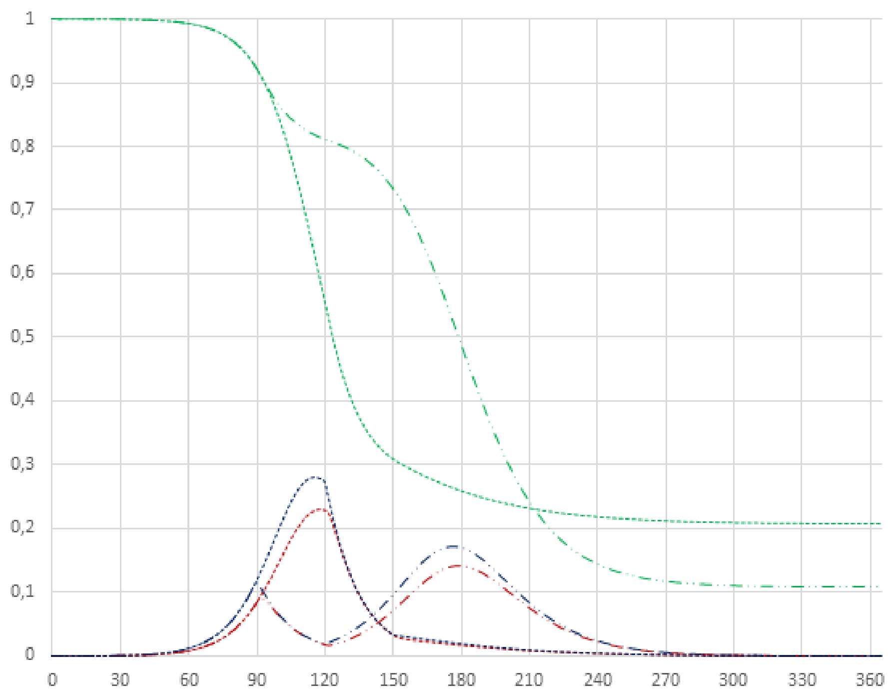

Figure 3. Pandemic dynamics for 30 day quarantines covering 80 per cent of the population starting on days 90 and 120

The following two figures illustrate how the peak level of the share of infectious individuals and the day when this peak level is reached are affected by the timing of a thirty-day quarantine covering 80 per cent of the population; the horizontal axis measures the day of the pandemic when the quarantine starts.

[5] This case is discussed by Anderson et al. (2020).

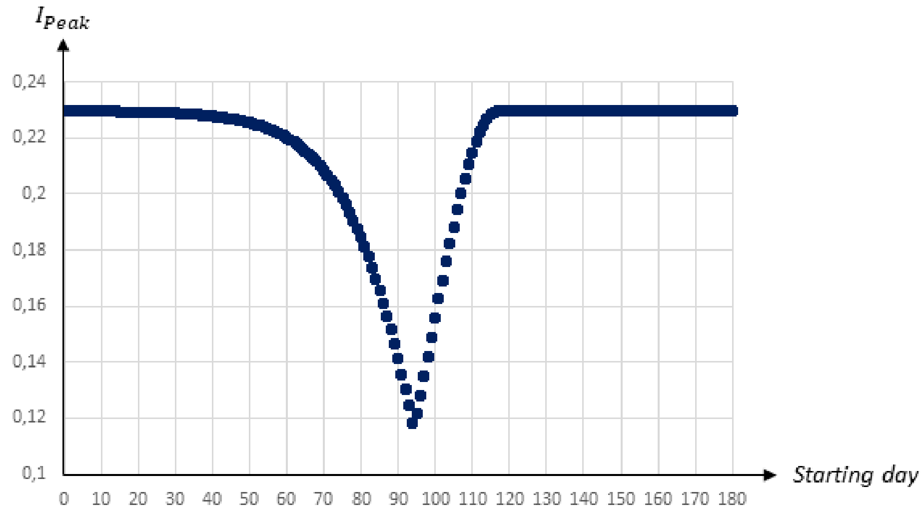

Figure 4. The peak level of infectious people in relation to the starting date of a 30 day quarantine covering 80 per cent of the population

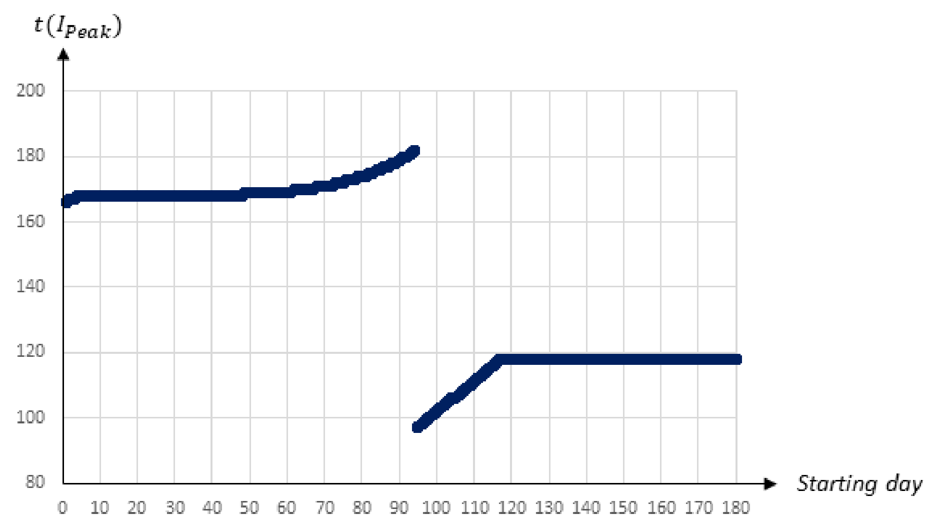

Figure 5. The day of the peak level of infectious people in relation to the starting date of a 30 day quarantine covering 80 per cent of the population

The perhaps most striking result is that there is a U-shaped relationship between the starting day of the quarantine and the maximum share of infectious individuals. An early quarantine primarily postpones the infection (see figure 2). Once lifted the infection runs its course, and, if there are still many susceptible in the population, the peak will be high. A late quarantine, just before or after the peak of the infection has passed, has no effect on the level of he peak (see figure 3). The peak of the infection is therefore mostly reduced by a quarantine in the midst of the pandemic. This results in a double peak in the share of infectious persons, leading to a drop in the peak day as the first peak becomes larger than the second peak.

In the example above a quarantine starting on day 94 seems optimal in terms of reducing the peak level of infectious individuals; it decreases to less than 12 percent from almost 23 percent in the absence of a quarantine. This is a remarkably stable result; although peak levels obviously depend on the duration and the extent of a quarantine, those starting around this date generally yield the lowest peak levels.[6]

The following figures show the share of population that has recovered after the pandemic as well as the economic losses with respect to the starting date.

[6] For a 30 day quarantine covering only 20 per cent of the population the I_{Peak}-level would reach its minimum if it is started on day 93; however, the minimum I_{Peak}-level would be somewhat higher, at 0.15.

For a 60 day quarantine covering 80 per cent of individuals the I_{Peak}-level would also reach its minimum if implemented on day 93; in this case the minimum I_{Peak}-level would be somewhat lower, at 0.1086.

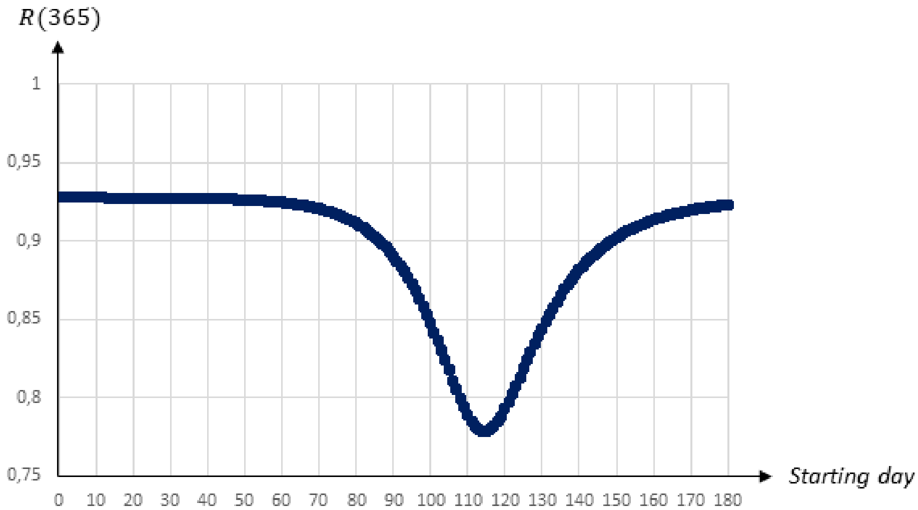

Figure 6. The share of population that has recovered one year after the start of the pandemic in relation to the starting date of a 30 day quarantine covering 80 per cent of the population

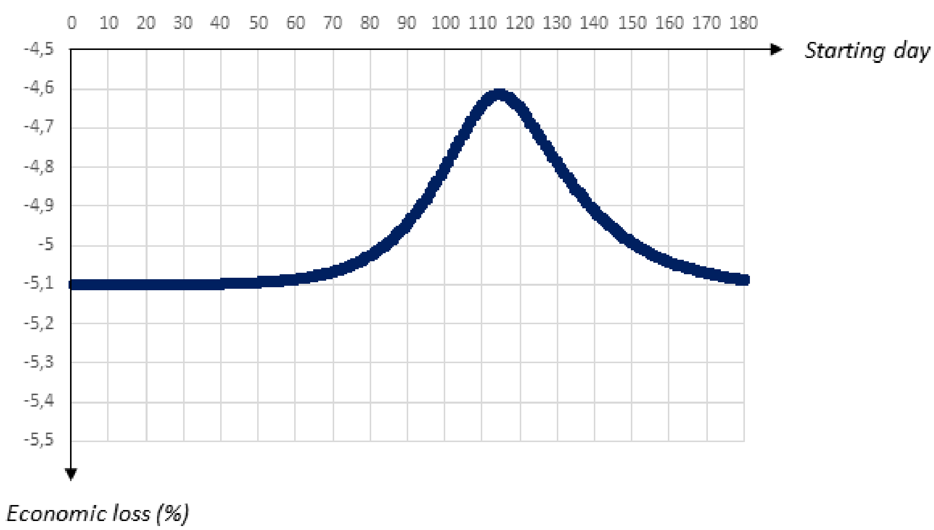

Figure 7. Economic losses in relation to the starting date of a 30 day quarantine covering 80 per cent of the population

There is a U-shaped relationship between the share of recovered individuals (and hence, also the share of deceased individuals) and the starting day of the quarantine. The lowest level is reached for a quarantine starting on day 114. In this case the share of the population that will have been infected and survived will be less than 78 per cent, as compared to almost 93 per cent in the absence of a quarantine. It is worth noting that herd immunity would be achieved for any 30 day quarantine covering 80 percent of the population, regardless of the starting day.[7]

The relationship between the economic loss and the starting date is also U-shaped, with economic losses minimized for a quarantine starting on day 115. Interestingly there seems to be no trade-off between economic losses and averting fatalities. The total number of deaths and the economic losses are both minimized when the quarantine is implemented around day 114-115. Thus, to keep fatalities as well as economic losses low it seems optimal to postpone a quarantine to just before the share of infectious individuals reaches its peak. Again this result is stable; obviously levels depend on the duration and extent of a quarantine, but the general pattern is similar.[8] The downside, however, is that this policy does little to reduce the peak, and the implementation of this policy is therefore dependent on there being sufficient capacity in the health care system.

To summarize, there is a trade-off between lowering the peak level of infectious people on the one hand, and reducing fatalities as well as economic losses on the other hand. If the main goal is to lower the I_{Peak}-level an earlier quarantine starting day within this time frame is preferable, while a later starting day would be optimal if the main goal is to reduce fatalities and/or economic losses. An implication of this is that a high capacity for intensive care treatment in the health care system implies that the government can chose a strategy that leads to both fewer deaths and lower economic losses.

3.2.2 Duration of the quarantine

We now turn to the effect of the duration of a quarantine. We simulate quarantines that covers 80 per cent of the population. As demonstrated in the previous section, the timing of a quarantine impacts crucially on the pandemic dynamics. To analyze the effects of a quarantines duration we therefore distinguish between those implemented early and those started later, when the share of infectious individuals starts taking off.

Consider first the case of a quarantine that starts at a relatively early stage of the pandemic. The following figure illustrates the pandemic dynamics in the absence of a quarantine (solid curves) and on day 60 of the pandemic with different durations (30 days: dashed curves; 60 days: dashed-dotted curves; 90 days: dotted curves).

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[7] The herd immunity threshold would be about 64% of the population given that $R_0 = 2.8$.

[8] For a 30 day quarantine covering only 20 per cent of the population the $R(365)$-value would be larger, reaching its minimum for one started on day 109 (at 0.875), while economic losses would be smaller, being minimized for a quarantine starting on day 111.

For a 60 day quarantine covering 80 per cent of individuals the $R(365)$-value would be smaller and minimized for one implemented on day 111 (at 0.668), while economic losses would be larger, being minimized for a quarantine starting on day 112.

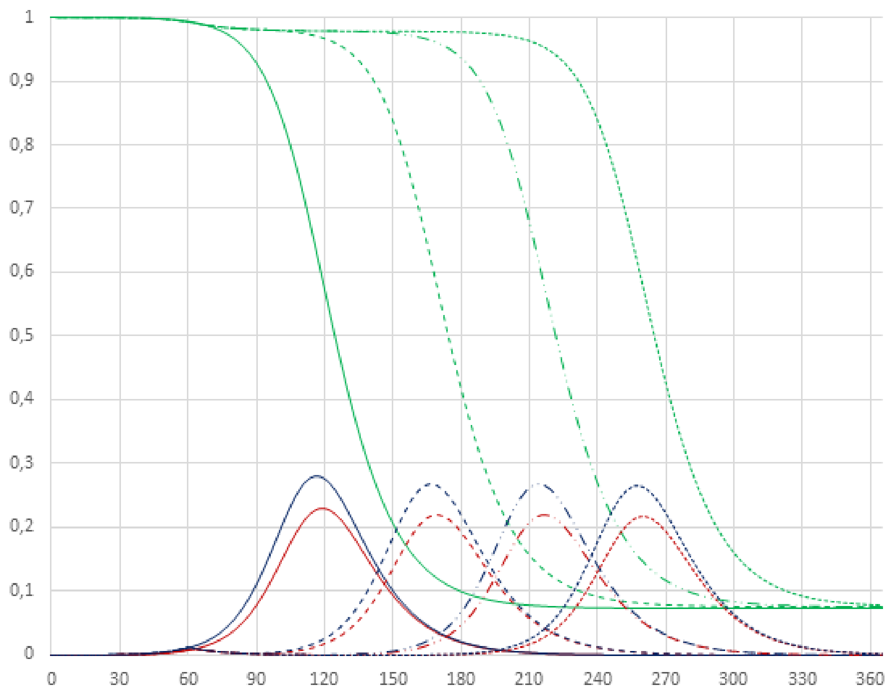

Figure 8. Pandemic dynamics for quarantines covering 80 per cent of the population starting on day 60 with different durations

The duration of a quarantine that starts relatively early, e.g. on day 60, pushes the dynamics forward, about 1.6 days per extra quarantine day, but has hardly any impact on the peak level of infectious individuals and the share of recovered persons after the pandemic has ended. Naturally a longer quarantine is associated with higher economic losses, about 0.1 percentage points for every extra day, as shown in the table below, which presents the I_{Peak}-level, the day when this peak is reached, the share of the population that will have been infected and survived, economic output and economic losses for quarantines of different durations. For example, Q60-74 indicates a quarantine starting on day 60 and ending on day 74.

Q60-, q=0,8	I_{Peak}	$t(I_{Peak})$	R(365)	Y	dY/Y
No quarantine	***0,229639***	***118***	***0,927533***	***359,2824***	***-1,83541***
Q60-74	0,222980	144	0,925365	353,3448	-3,45769
Q60-89	0,220134	169	0,924393	347,3839	-5,08635
Q60-104	0,218935	194	0,923933	341,4120	-6,71803
Q60-119	0,218358	217	0,923573	335,4361	-8,35078
Q60-149	0,217919	260	0,921169	323,4916	-11,6143

Table 1. Outcomes of quarantines of different durations, covering 80 per cent of the population and starting on day 60

A quarantine starting on the same day, but covering a smaller share of the population yields different results with respect to the duration. In particular, the share in isolation will impact substantially on the peak level, while having a smaller effect on the peak day and naturally leading to smaller economic losses (see section 3.2.3).

The impact of the duration of quarantines covering 80 per cent of the population is somewhat different when these start at a later stage, e.g. on day 90 of the pandemic, as illustrated in the following figure. The solid curves represent the absence of a quarantine, dashed curves represent a quarantine of 15 days duration, dashed-dotted curves represent a quarantine of 30 days duration and dotted curves represent a quarantine of 60 days duration.

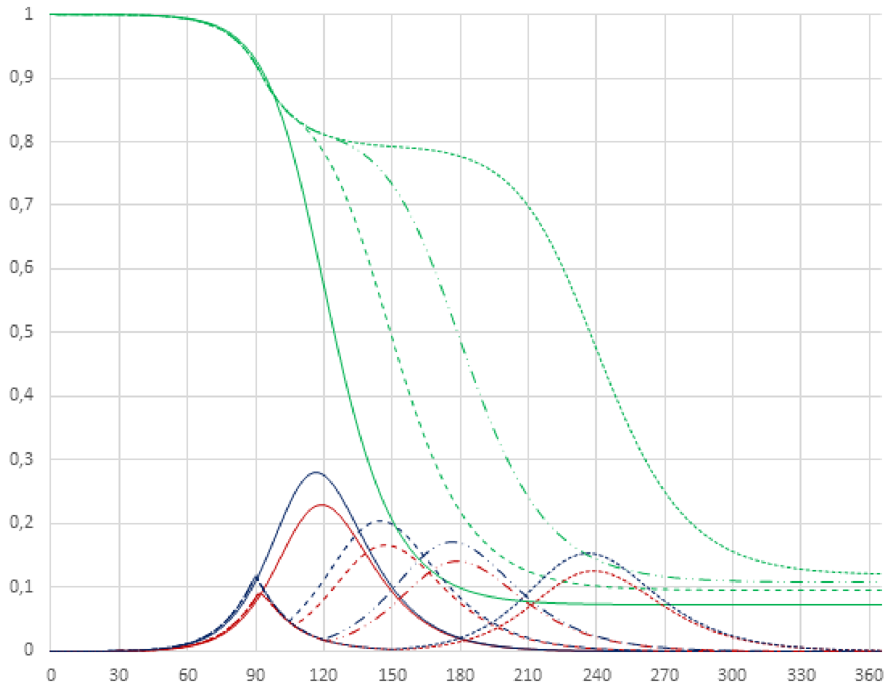

Figure 9. Pandemic dynamics for quarantines covering 80 per cent of the population starting on day 90 with different durations

All quarantines starting on day 90 lead to a double-peak in the share of infectious individuals, with the first peak occurring on day 90. The second, larger peak is pushed forward by around two days per extra quarantine day. The I_{Peak}-level decreases in the duration. The share of recovered individuals and deaths decrease in the duration of the quarantine. The following figures illustrate the impact of the duration (the number of days) of a quarantine on the peak level of infectious individuals and the day of the peak occurring.

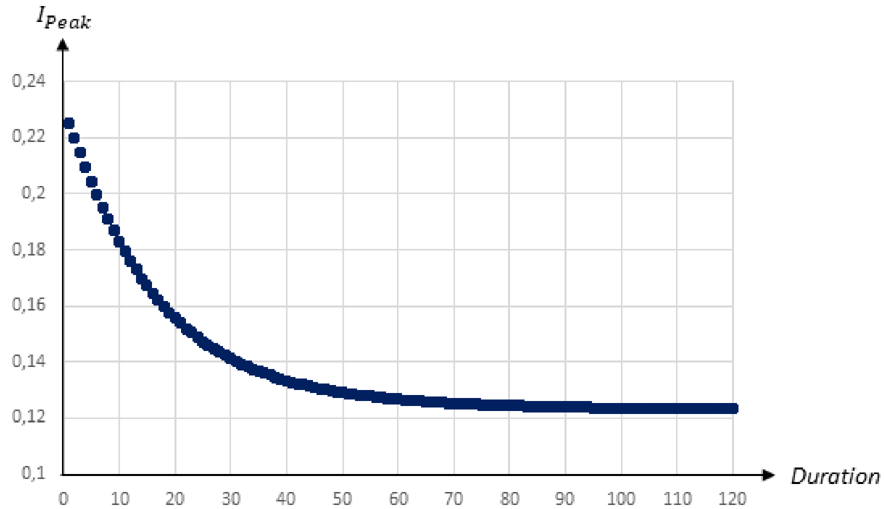

Figure 10. The peak level of infectious people in relation to the duration of a quarantine starting on day 90 and covering 80 per cent of the population

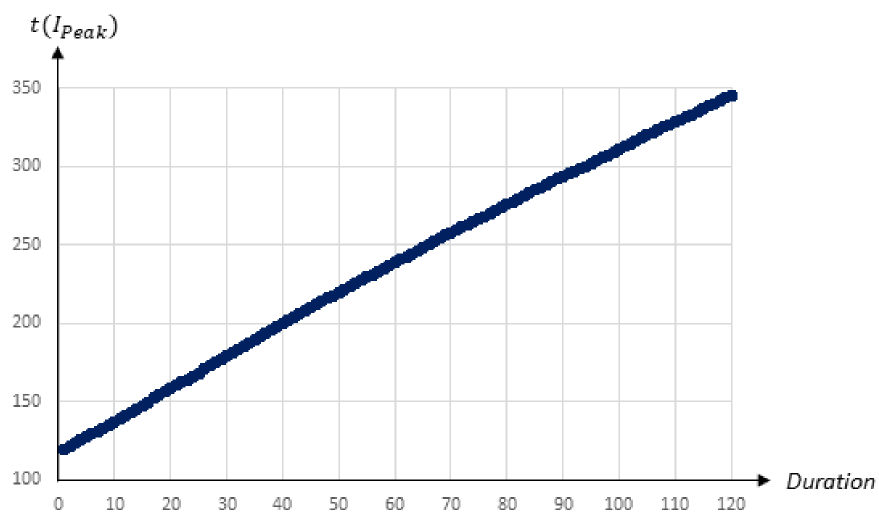

Figure 11. The day of the peak level of infectious people in relation to the duration of a quarantine starting on day 90 and covering 80 per cent of the population

While the peak day is almost linearly related to the duration, the peak level decreases at a decreasing rate in the duration. A quarantine lasting about 30 days reduces the peak level substantially; extending the quarantine beyond 30 days only marginally reduces the peak level, but pushes the peak date forward. The following two figures illustrate the impact on the share of recovered individuals after one year and the economic losses in relation to the duration; since quarantines starting on day 90 and lasting more than 60 days lead to the pandemic not having ended after one years time, only the effects for durations up to 60 days are presented.

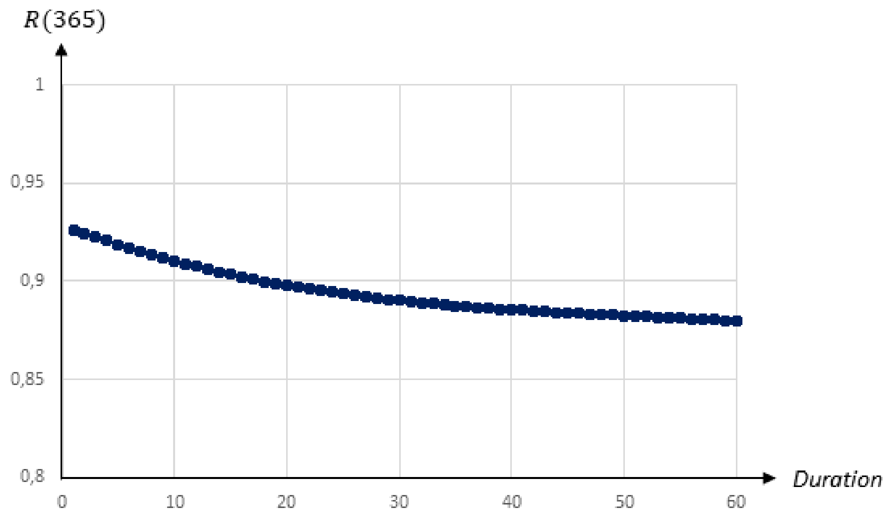

Figure 12. The share of population that has recovered one year after the start of the pandemic in relation to the duration of a quarantine starting on day 90 and covering 80 per cent of the population

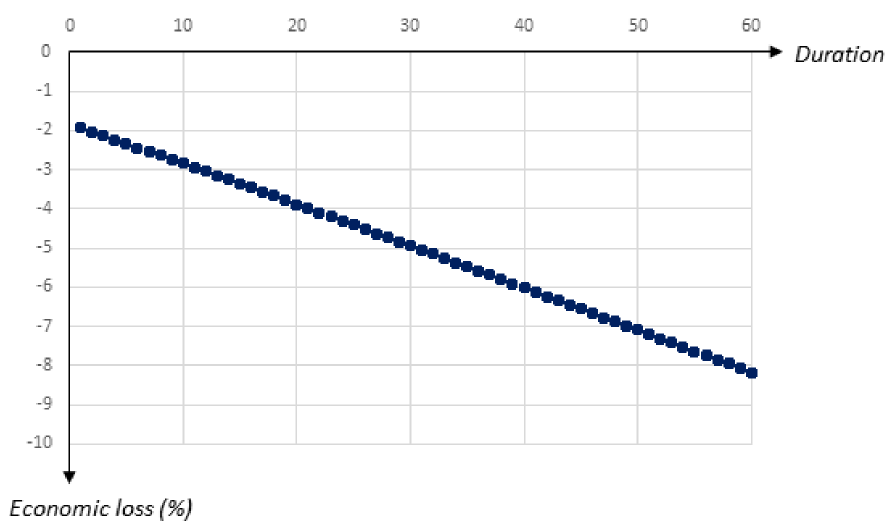

Figure 13. Economic losses in relation to duration of a quarantine starting on day 90 and covering 80 per cent of the population

The share of recovered individuals and hence, also the share of deceased persons is only marginally affected by the duration, whereas economic losses increase almost linearly in the duration, by more than 0.1 percentage points for every extra quarantine day.

To summarize, longer quarantines imply larger economic losses. The main effect of a longer duration of a quarantine that is implemented at an early stage of the pandemic is to push the infection forward. For quarantines that start later, the peak level of infectious individuals is reduced by a longer duration, and so is the number of recovered and dead individuals. Thus, there is a relatively clear trade-off between economic costs and health outcomes in terms of the duration of a quarantine.

3.2.3 Extent of the quarantine

Finally, we vary the share of the population that is covered by the quarantine, q. Again we distinguish between quarantines starting early on and those starting later during the pandemic.

First, we consider quarantines starting relatively early, e.g. on day 60, and lasting for 60 days. The following figure illustrates the pandemic dynamics in the absence of a quarantine (solid curves) as well as for quarantines covering different shares of the population (20 per cent: dashed curves; 40 per cent: dashed-dotted curves; 60 per cent: dotted curves).

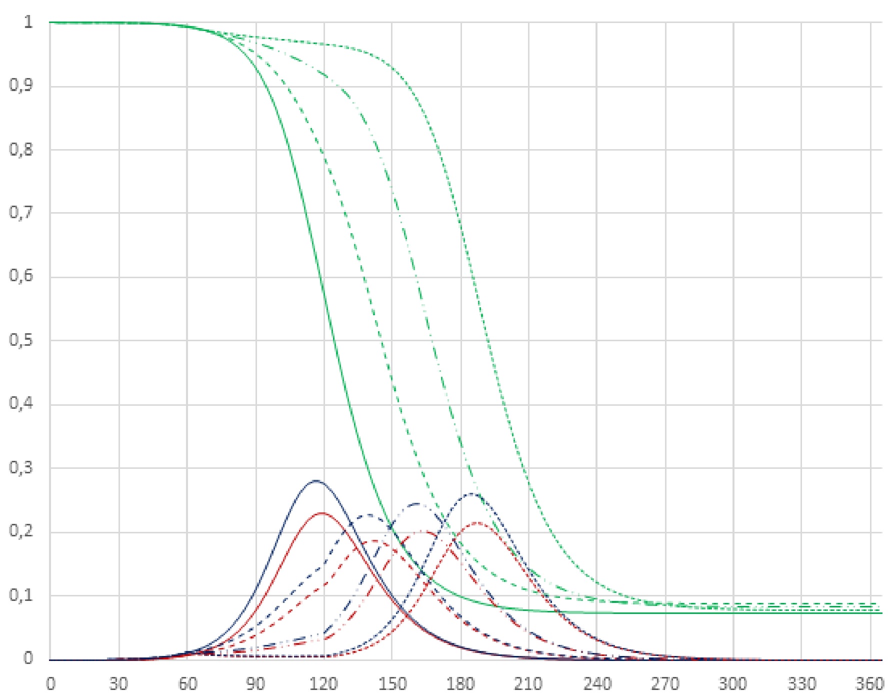

Figure 14. Pandemic dynamics for 60 day quarantines starting on day 60 and covering different shares of the population

An increase in the share of quarantined persons unambiguously pushes the I_{Peak}-day forward. The I_{Peak}-level first decreases somewhat, but eventually increases as a higher share of the population is covered by the quarantine. The share of recovered individuals remains stable above 90 per cent. The following table summarizes results of simulations; a quarantine covering the entire population is obviously not realistic, but can be used as a benchmark.

Q60-119	I_{Peak}	$t(I_{Peak})$	*R(365)*	*Y*	*dY/Y*
No quarantine	***0,229639***	***118***	***0,927533***	***359,2824***	***-1,83541***
q=0.2	0,185808	142	0,911491	353,4251	-3,43577
q=0.4	0,200683	163	0,917401	347,4115	-5,07882
q=0.6	0,213378	187	0,922015	341,4107	-6,71840
q=0.8	0,218358	217	0,923573	335,4361	-8,35078
q=1.0	0,219352	232	0,923614	329,4590	-9,98387

Table 2. Outcomes of quarantines of different extents, starting on day 60 and lasting for 60 days

Thus, the principal effect of increasing q for an early quarantine is to push the infection forward in time, but this is associated with substantial economic costs.

For quarantines starting a later stage of the pandemic the pattern is slightly different. The following figure illustrates the pandemic dynamics in the absence of a quarantine (solid curves) as well as for quarantines starting on day 90 of the pandemic, lasting for 60 days and covering different shares of the population (20 per cent: dashed curves; 35 per cent: dashed-dotted curves; 60 per cent: dotted curves).

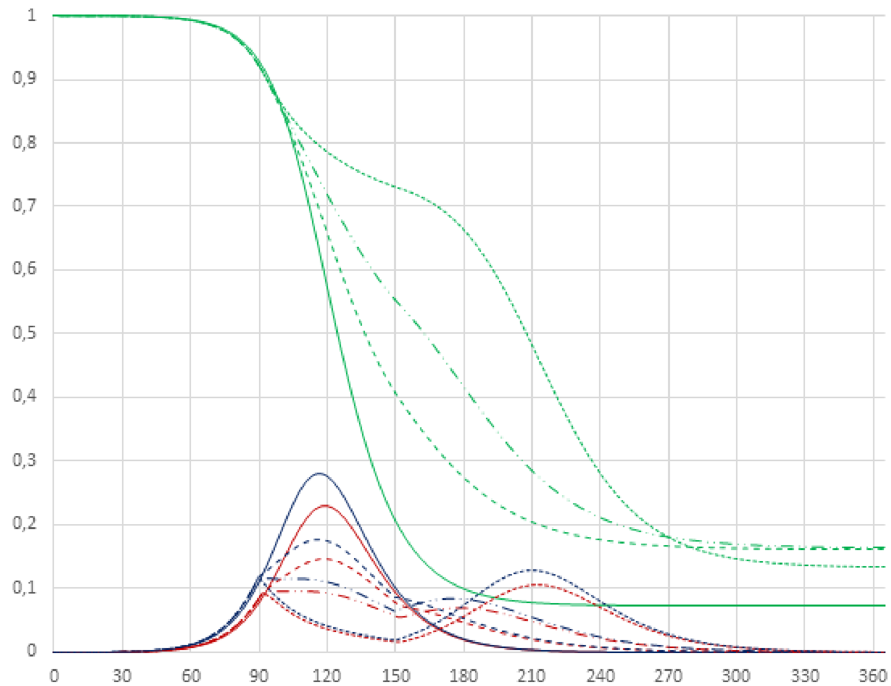

Figure 15. Pandemic dynamics for 60 day quarantines starting on day 90 and covering different shares of the population

A smaller share of quarantined individuals leads to flatter pandemic dynamics compared to the absence of a quarantine; in particular, the I_{Peak}-level is reduced substantially. For larger shares of quarantined individuals we obtain the familiar double-peak pattern, with the first peak occurring at the starting day of the quarantine. The second peak is actually lower for $q = 0.35$ than for $q = 0.6$, as a higher share will already have become infectious once the quarantine is terminated. The following figures illustrate how the I_{Peak}-level and the I_{Peak}-day are affected by the extent of the quarantine.

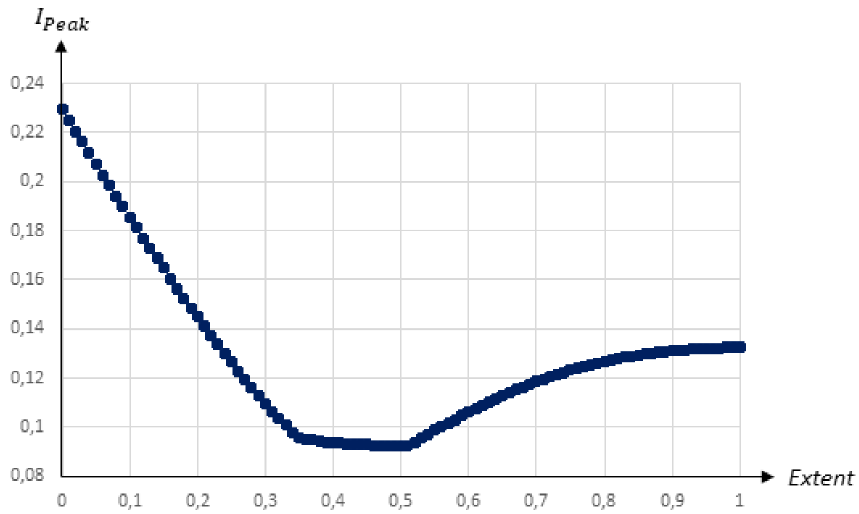

Figure 16. The peak level of infectious people in relation to the extent of a 60 day quarantine starting on day 90

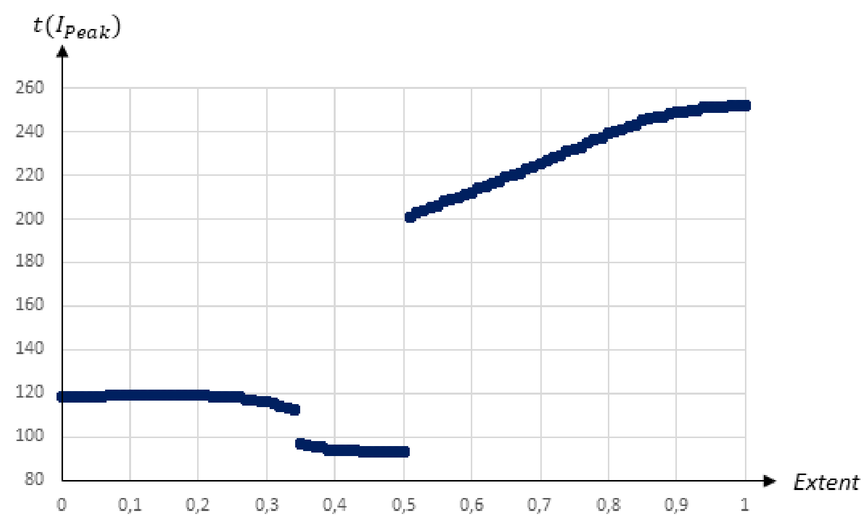

Figure 17. The day of the peak level of infectious people in relation to the extent of a 60 day quarantine starting on day 90

An increase in q initially reduces the I_{Peak}-level and has only a minor impact on the I_{Peak}-day.[9] Eventually an increase in q brings about the double-peaked pandemic pattern. A higher q is associated with an increase in the I_{Peak}-day, but also an increase in the I_{Peak}-level. The impact on the I_{Peak}-level is thus U-shaped, with a minimum reached for $q = 0.5$ when the two

[9] Note that for quarantines covering around a third of the population the first peak resembles a plateau lasting for almost 30 days (see figure 15 when $q = 0.35$). We therefore observe a drop in the peak-level day when q increases from 0.34 to 0.35, as the peak of this plateau shifts from day 112 to day 97.

peaks reach almost the same level. The following figures illustrate how the share of recovered individuals after one year and economic losses are affected by the extent of the quarantine.

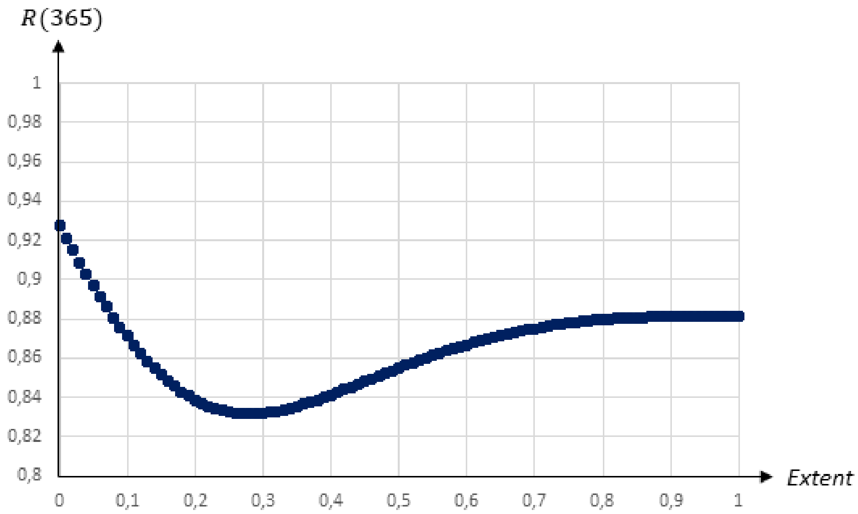

Figure 18. The share of population that has recovered one year after the start of the pandemic in relation to the extent of a 60 day quarantine starting on day 90

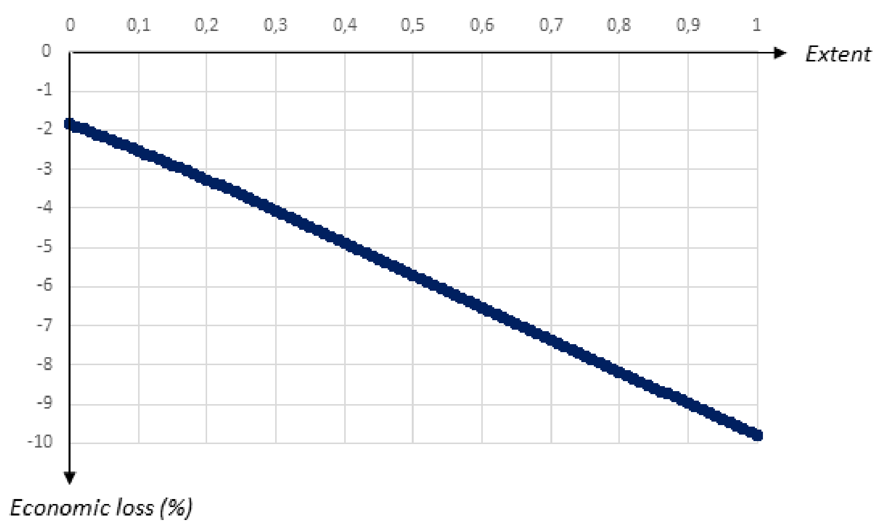

Figure 19. Economic losses in relation to the extent of a 60 day quarantine starting on day 90

The relationship between the share of recovered (and hence, also deceased) people after the pandemic and the extent of the quarantine is also U-shaped. More specifically, the number of deceased individuals is minimized for $q = 0.28$. Economic losses increase almost linearly in the share of quarantined persons, by almost 0.08 percentage points for every extra per cent being quarantined.

For $q \in [0.28, 0.5]$ there is a trade-off between lowering the I_{Peak}-level on the one hand and reducing the share of people that will have become exposed to the virus on the other hand. If the main goal is to minimize fatalities, a quarantine covering a smaller share of the population is optimal, while a quarantine covering almost half the population is preferable if the focus is on reducing the I_{Peak}-level.

To summarize, the main effect of increasing the share of the quarantined population when the quarantine starts at a relatively early stage of the pandemic is essentially that the peak infection day is pushed forward, but this comes at a substantial economic cost. A quarantine starting at a later stage, when the number of infectious individuals starts increasing rapidly, is associated with a U-shaped relationship between the peak level of infectious individuals and the extent of the quarantine, such that the peak level is reduced substantially for quarantines covering about half the population. At higher q-levels the peak is pushed forward, but this also leads to a higher peak level and higher economic losses. The share of deceased people is minimized for quarantines covering a rather small share of the population. Thus, there is a relatively strong case for limiting the extent of a quarantine, since this leads to a lower peak, fewer deaths and lower economic costs. However, such a policy would lead to an earlier peak of infectious people.

4 Conclusions

This paper considers some of the basic trade-offs between health outcomes and economic outcomes when a quarantine is implemented. For this purpose we employ a SEIR-model, calibrated to resemble the COVID-19 pandemic and coupled with the assumption that infected and quarantined individuals lose part of their productivity.

Our main findings can be summarized as follows. First, the implementation of an early quarantine will essentially postpone but not alter the course of the infection at a cost that increases in the duration and the extent of the quarantine. Second, a later starting day of a quarantine is optimal if the main goal is to reduce fatalities and economic losses, but it comes at the cost of a higher peak level of infectious people. The use of this strategy therefore depends on whether the health care system can deal with a high peak level. Third, there is a trade-off between economic costs and health outcomes when it comes to the duration of a quarantine. A longer quarantine either postpone the peak (if it is implemented relatively early) or dampens the peak and reduces deaths (if it starts at a later stage of the pandemic), but implies higher economic losses. Finally, there is a relatively strong case for limiting the extent of a quarantine. A less than complete quarantine leads to a lower peak, fewer deaths and lower economic costs. The flip side of this strategy is that the peak of infectious individuals occurs earlier.

To test the robustness of our results we have simulated pandemics with both higher and lower transmission rates. Qualitatively all our findings can be replicated for different pandemic dynamics. Thus, our conclusions regarding the timing, duration and extent of quarantines hold generally.

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