Initiative Model antiCOVID-19 for the Czech Republic

MODEL A

A Technical Description

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On the Epidemiological Model for the Czech Republic

Model A

1 Model A

Our model builds on a standard SEIR model structure in which agents pass through the model in several stages. The main goal of the baseline model A is to capture general trends in epidemiological developments in the 2020 COVID-19 pandemic in the Czech Republic and to quantify the effects of policies (e.g. smart quarantine and lock-down) on these trends. Due to its limited granularity in terms of regional and demographic structure, the model does not allow us to evaluate policies targeted at specific sub-populations or regions.

1.1 Structure

Ours is a one-country, one-population SEIR model in which all agents (citizens) at the starting point are denoted as healthy and **susceptible** (S) to disease. To start the spread of illness in the model, we have to import infectious agents from abroad[1]. After being infected, agents are denoted as **exposed** (E) and after an incubation period of 5 days they become **infectious** (I). Eventually, everyone who was exposed will either **recover** (R) or **die** (D). Recovered patients become immune and are not susceptible.

The model assumes two types of infectious agents - symptomatic (I_S) and asymptomatic (I_N). Each group of agents is treated differently by the model. Agents considered symptomatic will always be identified by state authorities on or before the 5th day of being infectious. The probability of being identified depends on how long s/he has been infectious. In particular, there are five parameters $cd^1, cd^2, cd^3, cd^4, cd^5$ that represent the probability of being detected on day 1, 2, 3, 4, and 5, respectively. The asymptomatic cases are assumed to be less likely to be isolated from the general population and thus are expected to spread the infection over a longer time period. In particular, we assume that asymptomatic carriers will

[1]Numbers are based on official reports from regional hygienic stations, available at `https://onemocneni-aktualne.mzcr.cz/api/v1/covid-19/osoby.csv`

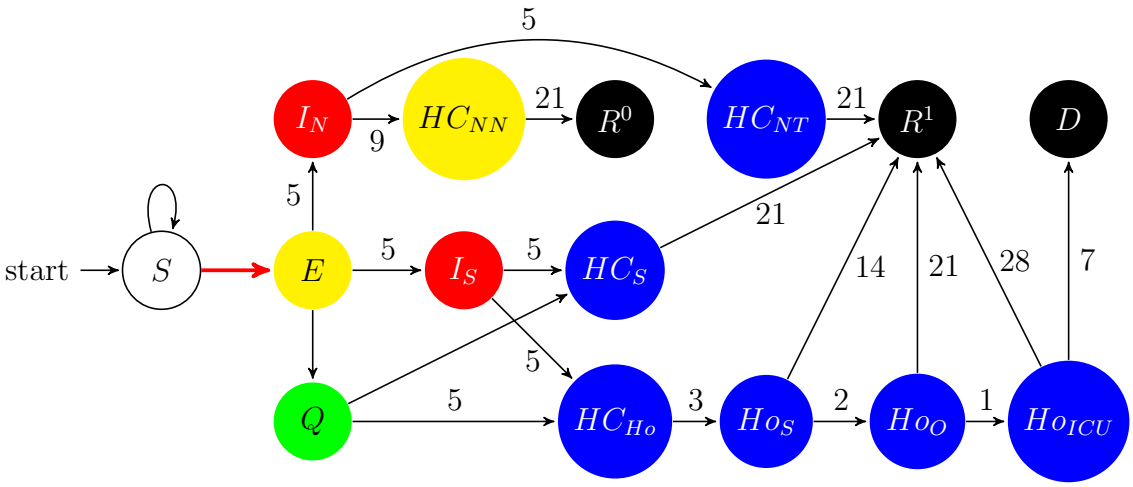
stop being infectious on or before the 9th day and the probability of stopping on a particular day is captured by a vector of parameters $dd^1, \ldots, dd^9$.[2] To capture the effect of policies introduced (e.g. increased testing capacity), the model can treat a share of asymptomatic cases (*par*) as if they were symptomatic. This is done by dividing I_N into two groups: infectious asymptomatic tested I_{NT} (*par*) and infectious asymptomatic non-tested I_{NN} (1- *par*).

We extend the standard framework by including **smart quarantine**. Smart quarantine effectively adds a new stage to the model - quarantine - in which we can lock away exposed agents before they become infectious and keep them isolated until they are no longer infectious. After 5 days in quarantine agents continue in the model as identified infectious. Agents kept in quarantine are identified earlier than they would be without the smart quarantine. Therefore, introduction of the smart quarantine will cause a temporary increase in reported cases of disease.

Figure 1 shows a simplified scheme of the model. Except for infectious agents from abroad, everyone starts out healthy, at stage S. Infected agents E: (i) become asymptomatic infectious I_N; (ii) become symptomatic infectious I_S; or (iii) are put into quarantine, if smart quarantine is introduced. For asymptomatic agents there are two different paths through which they can exit the model. First, a share of them will remain hidden to state authorities, will spread the infection in the population for up to 9 days, and then recover in 3 weeks (R^0). These agents will never be counted by state authorities. Second, the rest of the asymptomatic agents will be treated as symptomatic, will be identified by state authorities on or before the 5th day, isolated and will recover at home in 3 weeks (R^1).

[2]Asymptomatic patients are treated only at home and then recover. To map this process to the official statistics, one can think about asymptomatic person being infectious for up to 9 days and then becoming part of the 'invisible' recovered patients who now have immunity.

Figure 1: Epidemiological scheme of the model



Symptomatic cases I_S are divided into: (i) a group for whom home care is sufficient (denoted as HC_S) and who will recover in 3 weeks; and (ii) a group who require hospital admission. The latter do not go to the hospital immediately; they first stay home for 3 days (denoted as HC_{Ho}). Then they progress to the stage of standard hospitalization (denoted as Ho_S), from which they either recover or become more severe cases requiring oxygen (denoted as Ho_O). Next, from the oxygen stage, agents either recover or progress to the intensive care unit (denoted as Ho_{ICU}). Finally, from the ICU stage patients either recover or die. In the model, agents may die only after 7 days in the ICU stage. Calibration of transition matrix between different stages is based on corresponding probabilities estimated in international literature. See Table 2.

Note that the stages in blue nodes (and quarantine, if applicable) account for active cases that state authorities are aware of, the red stages represent infectious cases, and yellow ones are people who are infected, but not infectious. To keep the scheme uncluttered, we omit a few channels and sub-stages that are less important for understanding the model mechanism.

1.2 Formal Description

The model is formally described in equations (1) - (30). Parameters used in the equations are described in detail below. For each stage of the model, we generate sub-stages which represent one day spent in that stage. For example, since going through the **exposed** stage takes 5 days, we have 5 different sub-stages, one for each day. We apply this approach to all stages for which it is relevant. Each sub-stage is denoted by a superscript representing the day in that particular stage. Equations (31) - (33) describe the evolution of auxiliary variables of the model, e.g. increasing the effectiveness of smart quarantine over time.

Table 1: Notation of SEIR Stages in Equations

Name	Notation	(max) # days
Susceptible (Healthy)	S	
Exposed	E	5
Infectious	I	5
Infectious Symptomatic	I_S	5
Infectious Asymptomatic Tested	I_{NT}	5
Infectious Asymptomatic Nontested	I_{NN}	9
Homecare Asymptomatic Tested	HC_{NT}	21
Homecare (will) Recover	HC_R	21
Homecare (will need) Hospital	HC_{Ho}	3
Hospital (will need) Oxygen	Ho_O	2
Hospital Standard (will) Recover	Ho_{SR}	14
Hospital Oxygen (will need) ICU	Ho_{OICU}	1
Hospital Oxygen (will) Recover	Ho_{OR}	21
Hospital ICU (will) Recover	Ho_{ICUR}	28
Hospital ICU (will) Die	Ho_{ICUD}	7
Death	D	
Recovery	R	
Quarantine	Q	5

$$S[t+1] = S[t] * \left(1 - \frac{c27 * (1 - EfLockdown[t+1]) * I[t]}{c24 * Pop}\right) - import[t] \quad (1)$$

$$E[t+1] = \frac{c27 * (1 - EfLockdown[t+1]) * I[t] * S[t]}{c24 * Pop} + import[t] \quad (2)$$

$$E^k[t+1] = E^{k-1}[t]; \quad k \in \{2,3,4,5\} \quad (3)$$

$$I_S^1[t+1] = E^5[t] * (1 - c26) * (1 - ed1) \quad (4)$$

$$I_S^k[t+1] = I_S^{k-1}[t] * (1 - cd^k); \quad k \in \{2,3,4,5\} \quad (5)$$

$$I_{NT}^1[t+1] = E^5[t] * c26 * par * (1 - ed1) \quad (6)$$

$$I_{NT}^k[t+1] = I_{NT}^{k-1}[t] * (1 - cd^k); \quad k \in \{2,3,4,5\} \quad (7)$$

$$I_{NN}^1[t+1] = E^5[t] * c26 * (1 - par) * (1 - ed1) \quad (8)$$

$$I_{NN}^k[t+1] = I_{NN}^{k-1}[t] * (1 - dd^k); \quad k \in \{2,\ldots,9\} \quad (9)$$

$$Q^1[t+1] = E^5[t] * ed1_t \quad (10)$$

$$Q^k[t+1] = Q^{k-1}[t] \quad k \in \{2,3,4,5\} \quad (11)$$

$$HC_R^1[t+1] = (1 - c40) * Diagnosed_t \quad (12)$$

$$HC_R^k[t+1] = HC_R^{k-1}[t]; \quad k \in \{2,\ldots,21\} \quad (13)$$

$$HC_{Ho}^1[t+1] = c40 * Diagnosed_t \quad (14)$$

$$HC_{Ho}^k[t+1] = HC_{Ho}^{k-1}[t]; \quad k \in \{2,3\} \quad (15)$$

$$HC_{NT}^1[t+1] = \sum_{k=1}^{9} (I_{NN}^k[t] * dd^k) \quad (16)$$

$$HC_{NT}^k[t+1] = HC_{NT}^{k-1}[t] \quad k \in \{2,\ldots,21\} \quad (17)$$

$$Ho_O^1[t+1] = HC_{Ho}^3[t] * \frac{c41}{c40} \tag{18}$$

$$Ho_O^2[t+1] = Ho_O^1[t] \tag{19}$$

$$Ho_{SR}^1[t+1] = HC_{Ho}^3[t] * \left(1 - \frac{c41}{c40}\right) \tag{20}$$

$$Ho_{SR}^k[t+1] = Ho_{SR}^{k-1}[t] \quad k \in \{2, \dots 14\} \tag{21}$$

$$Ho_{OICU}[t+1] = Ho_O^2[t] * \frac{c42}{c41} \tag{22}$$

$$Ho_{OR}^1[t+1] = Ho_O^2[t] * \left(1 - \frac{c42}{c41}\right) \tag{23}$$

$$Ho_{OR}^k[t+1] = Ho_{OR}^{k-1}[t] \quad k \in \{2, \dots, 21\} \tag{24}$$

$$Ho_{ICUR}^1[t+1] = Ho_{OICU}[t] * \left(1 - \frac{c43}{c42}\right) \tag{25}$$

$$Ho_{ICUR}^k[t+1] = Ho_{ICUR}^{k-1}[t] \quad k \in \{2, \dots, 28\} \tag{26}$$

$$Ho_{ICUD}^1[t+1] = Ho_{OICU}[t] * \frac{c43}{c42} \tag{27}$$

$$Ho_{ICUD}^k[t+1] = Ho_{ICUD}^{k-1}[t] \quad k \in \{2, \dots, 7\} \tag{28}$$

$$Death[t+1] = Death[t] + Ho_{ICUD}^7[t] \tag{29}$$

$$\begin{aligned} Recovery[t+1] = Recovery[t] + Ho_{ICUR}^{28}[t] + HC_{NT}^{21}[t] + \\ + Ho_{OR}^{21}[t] + Ho_{SR}^{14}[t] + HC_R^{21}[t] \end{aligned} \tag{30}$$

$$Diagnosed[t] = Q^5[t] + \sum_k^4 (I_S^k[t] * cd^k) + I_S^5[t] + \sum_k^4 (I_{NT}^k[t] * cd^k) + I_{NT}^5[t] \tag{31}$$

$$Infectious[t] = \sum_k^5 I_S^k[t] + \sum_k^5 I_{NT}^k[t] + \sum_k^9 I_{NN}^k[t] \tag{32}$$

$$ed1[t] = \min\left\{ced1, \frac{ced1 * (1 + t - csmart)}{nabehchk + 1}\right\} \tag{33}$$

Parameters To run the model, there are several exogenous parameters that need to be specified. We classify them into two groups. First, some of the parameters, such as the share of asymptomatic cases or the basic R_0 are likely to be similar in different countries and thus can be based on data from international literature.

- **Basic** R_0: This denotes the number of people who are infected by one infectious person over the course of his illness in the absence of policy measures. MLE estimates based on data from the Diamond Princess cruise ship outbreak estimate it in the range of 2.06-2.52 (Zhang et al. (2020)), which is consistent with previously published estimates from China (Li et al. (2020b), Zhao et al. (2020)). The estimation on the general population, however, assumes that all cases are revealed and reported, which is highly improbable due to the existence of asymptomatic individuals. Therefore, even higher values of R_0 can be considered, as has been done in the study of the spread of disease within European countries by Imperial College London (Flaxman et al. (2020)).

- **Share of asymptomatic cases:** Probably the most reliable estimates are those from the Diamond Princess cruise ship outbreak. Moriarty (2020) report that of all who tested positive for the disease, 46.5 % were asymptomatic at the time of testing, and Mizumoto et al. (2020) provide similar results with asymptomatic carriers ranging between 45 and 50 %. Since most of those who tested positive were older than 60[3], the external validity of these statistics is questionable. Finally, Nishiura et al. (2020) estimates that fewer than half of COVID-19-infected individuals are asymptomatic. Similar conclusions can be derived from a survey of the Icelandic population[4] and testing in the Italian city of Vu[5]. Overall, based on the results of these studies, we

[3]To the best of our knowledge, the age composition is available only for those who tested positive.
[4]https://edition.cnn.com/2020/04/01/europe/iceland-testing-coronavirus-intl/index.html
[5]https://www.repubblica.it/salute/medicina-e-ricerca/2020/03/16/news/coronavirus_

assume that the share of asymptomatic cases is around 50 %, however, this figure seems to be sensitive to testing conditions and the sample tested.

- **Incubation period:** Li et al. (2020a) and Lauer et al. (2020) found that the average incubation period is 5.2 and 5.1 days, respectively. The literature also suggests that the period varies greatly among patients. In particular, the WHO reports that the incubation period ranges from 2 - 10 days[6] and according to the CDC, the period ranges from 2 - 14 days[7]. In our model, agents stay exposed but not infectious for 5 days, during which they can be quarantined.

The second group of parameters that quantify the effectiveness of policy measures introduced are difficult to learn from literature, as different countries have adopted different sets of measures and citizens of different countries may respond differently to policies. To determine these values, we rely on our best expert judgment. Introduction of republic-wide smart quarantine is expected on 27 April 2020. We expect that it will take three weeks before smart quarantine will operate on its maximal effectiveness. Parameters of the effectiveness of lock-down and smart quarantine are of the least identified parameters in the model. At this stage, we re-calibrate them on a weekly basis to reach the best fit on updated statistics. Further methods of calibration are considered in the extension.

Import To initiate the model, we import cases from abroad. Each officially reported case is shifted back by 8 days which represent the incubation period and the time needed to get tested. For each of the reported case, we add two additional asymptomatic ones. This leads to 66 % of imports being asymptomatic cases, which is more than the model assumes for the

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[6] https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200127-sitrep-7-2019--ncov.pdf

[7] https://www.cdc.gov/coronavirus/2019-ncov/symptoms-testing/symptoms.html?CDC_AA_refVal=https%3A%2F%2Fwww.cdc.gov%2Fcoronavirus%2F2019-ncov%2Fabout%2Fsymptoms.html

Table 2: List of Parameters

Population	Pop	10 647 720
Share of asymptomatic	$c26$	0.5
Prob of tested symptomatic	$cd^1 - cd^5$	(0.05 0.1 0.15 0.3 0.4)
Prob of tested asymptomatic	$dd^1 - dd^9$	(0.05 0.05 0.05 0.05 0.1 0.1 0.1 0.2 0.3)
Prob of treated asymp. as symp.	par	0.2
Basic R0	$c27$	2.5
Infection period	$c24$	5
Share: hospital given diagnosis	$c40$	0.15
Share: oxygen given diagnosis	$c41$	0.045
Share: ventilation given diagnosis	$c42$	0.03
Death rate	$c43$	0.02
Start of SQ	$csmart$	27.4.2020
Max effectiveness of SQ	$ced1$	0.6
Duration until full SQ	$nabehchk$	21 (days)
Effectiveness of lock-down (t)	$EfLockdown$	0.85

general population (50 %). There are two reasons we believe this is a reasonable approach. First, most of the imports are skiers who became infected in Italy and who are statistically younger and fitter, and thus less likely to be symptomatic cases or to get tested voluntarily. Second, since February, the attention of citizens to COVID-19 has dramatically increased, and thus more people (even those with very mild symptoms) are more likely to get tested, either because of their own choice or through the effect of quarantine.

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