Lodz Economics Working Papers

To freeze or not to freeze? Epidemic prevention and control in the DSGE model with agent-based epidemic component

Jagoda Kaszowska-Mojsa,
Przemysław Włodarczyk

3/2020

FACULTY OF ECONOMICS AND SOCIOLOGY
University of LODZ

Article

To freeze or not to freeze? Epidemic prevention and control in the DSGE model with agent-based epidemic component

Jagoda Kaszowska-Mojsa [1,‡] and Przemysław Włodarczyk [2,‡]

[1] Institute of Economics Polish Academy of Sciences; jagoda.kaszowska@inepan.waw.pl
[2] University of Łódź, Faculty of Economics and Sociology, Department of Macroeconomics; przemyslaw.wlodarczyk@uni.lodz.pl
‡ These authors contributed equally to this work.

Version 31 October 2020

Abstract: The ongoing epidemic of COVID-19 raises numerous questions concerning the shape and range of state interventions, that are aimed at reduction of the number of infections and deaths. The lockdowns, which became the most popular response worldwide, are assessed as being an outdated and economically inefficient way to fight the disease. However, in the absence of efficient cures and vaccines they lack viable alternatives.
In this paper we assess the economic consequences of epidemic prevention and control schemes that were introduced in order to respond to the COVID-19 outburst. The analyses report the results of epidemic simulations obtained with the agent-based modeling methods under different response schemes and use them in order to provide conditional forecasts of standard economic variables. The forecasts are obtained from the DSGE model with labour market component.

Keywords: COVID-19; agent-based modelling; dynamic stochastic general equilibrium models; scenario analyses

1. Introduction

The first months of 2020 brought the world to almost a complete halt due to the occurrence and outbreak of the SARS-CoV-2 coronavirus, responsible for development of a highly lethal COVID-19 disease. Despite the hopes that vigorously developing medical sciences will quickly find effective remedy, last months made it quite clear that such a turn of events is not very likely. As of today, we still lack proper medical treatments which would significantly increase the survival rate of COVID-19 patients, while the vaccine is still in the phase of tests and thus rather a remote perspective. In such a situation the question concerning the shape and range of state interventions aimed at reduction of the number of infections and deaths becomes of paramount importance.

Lockdowns of various scale and composition were introduced in the majority of developed economies in order to decrease the transmission of the virus and reduce the hospital occupancy rates. Some countries decided to close the economy abruptly, the others did it on a step-by-step basis. The efficiency and economic impact of lockdowns differed depending on the social, cultural and economic characteristics of a given state. And so differed also their public reception. Up until today there are no clear guidelines on how should the lockdown policy be implemented. Therefore the two major questions addressed in the presented paper are:

- Should we freeze an economy in order to decrease the pace of SARS-CoV-2 transmission?

- What should be the scale and composition of an efficient lockdown policy?

Our attempt at explaining the macroeconomic consequences of COVID-19 epidemic and its potential countermeasures is not an exclusive one, as the topic became one of the scoops in economic literature. Therefore, we begin our article with a literature review on the impact of the COVID-19 epidemic on public health and the economy. In particular, we focus on the application of two methodologies also used in this article: agent-based models (ABM) and dynamic stochastic general equilibrium models (DSGE), some of which included the Susceptible-Infected-Recovered (SIR) component. In the section 3, we present our agent-based model which we use for scenario analysis. In section 4, we present four scenarios of the spread of coronavirus and the regulator's responses to the epidemiological and economic crisis. The ABM model is also used to generate the productivity shocks that feed the DSGE model in the following section. In section 5, we present the details of DSGE model that allows us to test the macroeconomic consequences of pandemics. In section 6, COVID-19 prevention and control schemes are compared in terms of their effectiveness. In section 7, we discuss the policy implications. The section 8 concludes.

2. Literature review

The impact of the coronavirus epidemic on society and the economy has recently been increasingly explored using very different methodologies, among which the predominant ones were SIR and agent-based approaches. In some cases, the SIR component has been an integral part of more complex computational simulation models. The SIR model was firstly successfully implemented into the DSGE model to study the COVID-19 pandemics by Eichenbaum et al. [4]. This model gained particular importance and popularity among central bankers in the first phase of the COVID-19 epidemics. The model implied that the containment policy increases the severity of the recession but saves roughly half a million lives in the U.S. The article demonstrated that the competitive equilibrium is not socially optimal because infected people do not fully internalize the effect of their economic decisions on the spread of the virus.

With reference to this article, Mihailov [5] estimated the Galí-Smets-Wouters (2012) model with indivisible labor for five major and most affected by the COVID-19 pandemic economies: the US, France, Germany, Italy and Spain. The author carried out a number of simulations that suggested the recoverable in 1-2 years loss of per-capita consumption and output in optimistic scenario, and the permanent output loss after the permanent labor supply shock that will still persist after 10-15 years in the pesimistic scenario.

The equilibrium model with multiple sectors Keynesian supply shocks, incomplete markets and liquidity constrained consumers was presented by Guerrieri et al. [10]. The authors opted for closing down contact-intensive sectors and providing full insurance payments to affected workers as an optimal policy that would allow us to achieve the first-best allocation, despite the lower per-dollar potency of fiscal policy.

The DSGE methodology, although without the explicit SIR component, was also used to examine the impact of the coranavirus outbreak on tourism and to test the policy of providing tourism consumption vouchers for residents [6].

In turn, Bayraktar et al. [7] developed an macroeconomic SIR model of the COVID-19 pandemic which explicitly considers herd immunity, behavior-dependent transmission rates, remote workers, and indirect externalities of lockdown. Likewise, using SIR model Brotherhood et al. [21] analysed the importance of testing and age-specific policies in face of the spread of the COVID-19 epidemic. The heterogeneous policy responses in terms of testing, confinements, and selective mixing by age group were examined by the authors. Also Toda [8] estimated the SIR component in the context of asset-pricing models paying attention not only to the consequences of the epidemics for the real economy, but also for the financial system.

In parallel to the development of the SIR model and the macroeconomic models with the SIR component, agent-based simulations have also been created. This approach allowed for more flexibility in the modeling process. Agent-based models have been used successfully in epidemic modeling in the past [1–3]. However, in this paper we focus only on the models of the spread of the epidemic and its medical and economic consequences elaborated in the last ten months as they relate directly to the COVID-19 pandemic.

Cuevas [11] elaborated an agent-based model to evaluate the COVID-19 transmission risks in facilities. Under the assumption that each agent maintains different mobility requirements and contagion susceptibility, Cuevas [11] tested the coexistence conditions that need to be imposed and habits that should be avoided for reducing the transmission risks.

An interesting combination of the advantages of ABM and SIR approaches was present in the model developed by Silva et al. [12]. The COVID-ABS model, a new SEIR (Susceptible-Exposed-Infected-Recovered) agent-based model aimed to simulate the pandemic dynamics using a society of agents emulating people, business and government. The authors developed scenarios of social distancing interventions, including the scenarios of lockdown or partial isolation, the use of face masks and the use of face masks together with 50% of adhesion to social isolation.

The course of the COVID-19 epidemic in smaller regions than countries was studied by Shamil et al. [13]. Their agent-based model was validated by comparing the simulation to the real data of American cities. The authors' experiments suggest that contact tracing via smartphones combined with a city-wide lock-down results in the effective counteractive measure (the reproduction number fell below 1 within three weeks of intervention in the scenario presented in the paper).

Hoertel et al. [14] examined the effectiveness of lockdown and the potential impact of post-lockdown measures, including physical distancing, mask-wearing and shielding individuals who are the most vulnerable to severe COVID-19 infection, on cumulative disease incidence and mortality, and on intensive care unit bed occupancy. The authors examined the conditions necessary to prevent a subsequent lockdown in France.

Wallentin et al. [15] discussed COVID-19 intervention scenarios for a long-term disease management. As it has been noticed the first outbreak of coronavirus disease was restrained in many countries around the world by means of a severe lockdown. Nonetheless, the second phase of disease management, the spread of the virus needs to be contained within the limits that national health systems can cope with. In this paper four scenarios were simulated for the so-called *new normality* using an agent-based model. The authors suggest contact-tracing as well as adaptive response strategies that would keep COVID-19 within limits.

Currie et al. [16] addressed the challenges resulting from the coronavirus pandemic and discussed how simulation modelling could help to support decision-makers in making the most informed decisions. Likewise, Bertozzi et al. [17] discussed the challenges of modeling and forecasting the spread of COVID-19. The authors presented the details of three regional-scale models for forecasting the course of the pandemic. Capable of measuring and forecasting the impacts of social distancing, these models highlight the dangers of relaxing nonpharmaceutical public health interventions in the absence of a vaccine.

Kloh et al. [18] studied the spread of epidemics in low income settings, given the special socioeconomic conditions surrounding Brazil. The authors applied the agent-based model to simulate how the public interventions can influence the spread of the virus in a heterogeneous population.

The purpose of Maziarz and Zach [19]'s work was to assess epidemiological agent-based models of the COVID-19 pandemic methodologically. The authors applied the model of the COVID-19 epidemic in Australia (AceMod) as a case study of the modelling practice. The main conclusion was that although epidemiological ABMs involve simplifications of various sorts, the key characteristics of social interactions and the spread of virus are represented accurately.

Kano et al. [20] addressed the interrelation between the spread of the virus and economic activities. The agent-based model was presented in which various economic activities were taken into account. The computational simulation recapitulated the trade-off between health and economic damage associated with lockdown measures.

Brottier [22] presented the shortcomings of the SEIR approach to study the spread of virus and emphasized the advantages of epidemic agent-based models. A more popular-science contribution, comparing the advantages and disadvantages of SIR and ABM models, was presented by Adam [23]. The strong points of the agent-based approach in epidemic modelling were also highlighted by Wolfram [24]. As many simple models of disease spread assume homogeneous populations (or population groups) with scalar interaction rates, Wolfram proposed different approach. The variability between agents in interactions rate and the structure of the in-person contact network was included in an agent-based model. The investigation of the properties of this model revealed that there is a critical point in the amount of interaction that determines whether everybody gets sick or nobody does. The structure of the contact network and the heterogeneity of agents also matters. The main finding of his article was that reducing interaction between group of agents increases the uncertainty in the outcome, but flattens the curve and reduces the average total number of people infected. It is also better to support the policies that allow for a number of small meetings that a few large ones.

Although in our article we attempt to estimate the impact of the epidemic on the society and economy in the short term (up to 2 years), it is also worth noting that in the literature the first attempts were made to estimate long-term effects of COVID-19 pandemic [9].

3. COVID-19 dynamics - ABM approach

We construct an agent-based model to simulate the spread of the COVID-19 virus and analyze the impact of the epidemic on society's overall labor productivity. We then use this model to run four simulations (see Section 3) and estimate the economic impact using dynamic stochastic general equilibrium model (see Section 4).

In the most basic version, the functioning of the model was defined in 6 modules, i.e. parts of the code. In the first module, basic parameters and initial conditions are adopted. The variables and parameters were explained in Tables 1 and 2. The values of these parameters and the probabilities were estimated on the basis of empirical data and are specific for a given epidemic scenario in a given country. The calibration for a given scenario is explained in Table 4.

The second module creates the matrices of society using initial parameters. In particular, the following were created:

- an $M \times T$ matrix $\boldsymbol{H}$ that records the health status of each agent in society after each iteration
- an $M \times T$ matrix $\boldsymbol{W}$ that records the productivity of each individual in the society after each iteration
- an $M \times T$ matrix $\boldsymbol{A}$ that records age of each individual in the society after each iteration
- an $M \times 2T$ matrix $\boldsymbol{X}$ that records location of each individual on the map after each iteration (x- & y-coordinates)
- an $M \times 4$ matrix $\boldsymbol{F}$ that records full data set

We assign randomly location, health status and age to each agent (the amount of infected people has already been set in initial conditions).

The third module describes the movements of the population (agents) in a closed economy. We use the logic known from cellular automata models. By default, in the basic model, a healthy individual moves in the Moore neighborhood of a cell (although this assumption can be modified easily). An infected person (symptomatically and asymptomatically) can move around and continue to infect other agents. When an agent is qualified as deceased, treated or in quarantine, it stops moving. It is worth noting that in calibrating the scenarios we use the size of the grid and the number of entities that provide the actual empirical population density of the selected country.

The fourth part defines the spread of coronavirus in the society. The code analyzes the neighborhood of each agent.

Cases for healthy individuals

If there is an infected ($s_t^{Ind} = 2$) or treated person ($s_t^{Ind} = 3$) in the neighborhood of a given individual, the healthy person ($s_t^{Ind} = 1$) may become infected ($s_t^{Ind} = 2$) or directly treated in the hospital (or put in the isolation) ($s_t^{Ind} = 3$) with a certain probability. If an agent is infected, it does not mean that it has been diagnosed as such. The code first checks if agent become infected (first probability test) and if the test was successful it checks if this individual has been diagnosed and directed for treatment (second probability test). For agents that has not been infected program checks if they have been directed for preventive quarantine ($s_t^{Ind} = 4$). With a certain probability, a healthy individual may die within one week ($s_t^{Ind} = 5$). The state transition probabilities in the agent-based epidemic component are described in Figure 1.

Cases for infected individuals

For people that are already infected ($s_t^{Ind} = 2$), system checks if they have been directed for treatment ($s_t^{Ind} = 3$), died ($s_t^{Ind} = 5$) or managed to conquer the virus ($s_t^{Ind} = 1$). As in previous case all the tests are probabilistic in nature.

Cases for treated or infected individuals in isolation

Agents undergoing treatment ($s_t^{Ind} = 3$) are reasonably likely to recover ($s_t^{Ind} = 1$), remain in hospital or in isolation ($s_t^{Ind} = 3$), or die of infection ($s_t^{Ind} = 5$) (with certain probabilities).

Cases for healthy individuals in preventive quarantine

For individuals in preventive quarantine ($s_t^{Ind} = 4$), the system checks the time agent has stayed in quarantine. After 2 weeks (2 iterations) the agent can be released based on probabilistic test. The individual may be healthy after the quarantine ($s_t^{Ind} = 1$). In addition, a probabilistic test is carried out to check whether the quarantined person has contracted the virus, e.g. as a result of contacts with the immediate family during or at the end of quarantine (respectively $s_t^{Ind} = 3$ and $s_t^{Ind} = 2$). With a very small probability, the individual may also die during the quarantine ($s_t^{Ind} = 5$)

It is also worth noticing that probability tests are taking into consideration age of an agent. Elderly people have higher probability of being infected or dying due to coronavirus infection. Changing the health status causes the agent's productivity to be updated accordingly. The decline of individuals' productivity was extensively discussed among authors and consulted with medical specialists. The input data is also consistent with the estimation results from the literature.

In the fifth module, aggregated values are calculated for each iteration, i.e.

- the productivity of the society
- the number of infected citizens by age
- the number of healthy individuals by age
- the number of agents under treatment by age
- the number of individuals in preventive quarantine by age
- the number of deceased by age.

We use this data to determine the productivity shock that feeds the dynamic stochastic general equilibrium model.

The last part of the code visualizes the results for a given simulation and describes the most important information in the output tables for further analysis using the DSGE model (especially data on the course of the epidemic and the productivity shocks).

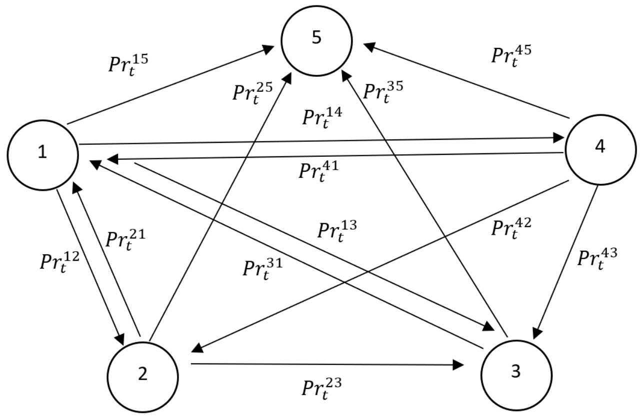

Figure 1. State transition probabilities in the agent-based epidemic component.

Table 1. Initial conditions/Parameters to be set

Initial conditions	Explanation	Restr.
T	Number of iterations (weeks) .	≥ 0
s_t^{Ind}	Health status of the individual at time $t = 0$ (1 - healthy, 2 - infected, 3 - treated, 4 - healthy individual in preventive quarantine, 5 - dead)	Int $\in \{1, 2, 3, 4, 5\}$
$(Age)_t^{Ind}$	Age of an individual at time $t = 0$	
N^{Ind}	Number of individuals at time $t = 0$	Int ≥ 0
K^{Ind}	Number of infected individuals at time $t = 0$ (including asymptomatically infected)	Int ≥ 0
$S_t \times S_t$	Dimensions of the grid at time t*	Int ≥ 0
$(Ag)_t^1$	Share of citizens of pre-working age at time t	≥ 0
$(Ag)_t^2$	Share of citizens of working age at time t	≥ 0
$(Ag)_t^3$	Share of retired individuals at time t	≥ 0
$(Wp)_t^{Ind}$	Productivity of an individual at time $t = 0$	$= 1$
$(Wp)_t^{av\_inf}$	The productivity of an individual when infected at time t (the decline in productivity was estimated based on empirical data)	≥ 0
$(Wp)_t^{av\_q}$	The productivity of an individual who is healthy and in quarantine at time t (the decline in productivity was estimated based on empirical data)	≥ 0
$(Wp)_t^{av\_t}$	The productivity of an individual when treated or who is infected and in quarantine at time t (the decline in productivity was estimated based on empirical data)	≥ 0

*The dimensions are not constant in all scenarios for all t. In baseline scenario $S_t = S$.

Table 2. Probabilities set as parameters*

Parameter	Explanation	Restr.
$(Pr)_t^{12}$	The probability that a healthy individual (1) will become infected (2) at time t	$\in (0,1)$
$(Pr)_t^{14}$	The probability that a healthy individual (1) will be in quarantine (although she is healthy) (4) at time t	$\in (0,1)$
$(Pr)_t^{15}$	The probability that a healthy individual (1) will become infected and dies almost instantly (within week) (5)	$\in (0,1)$
$(Pr)_t^{21}$	The probability that an infected individual (2) will become healthy (1)	$\in (0,1)$
$(Pr)_t^{23}$	The probability that an infected individual (2) will be treated in a hospital or will stay in quarantine (3)	$\in (0,1)$
$(Pr)_t^{25}$	The probability that an infected individual (2) dies (5)	$\in (0,1)$
$(Pr)_t^{31}$	The probability that an infected individual in a hospital or quarantine (3) gets better (1)	$\in (0,1)$
$(Pr)_t^{35}$	The probability that an infected individual in a hospital or quarantine (3) dies (5)	$\in (0,1)$
$(Pr)_t^{41}$	The probability that a healthy individual in quarantine (4) will end the quarantine, i.e. is healthy (1)	$\in (0,1)$
$(Pr)_t^{43}$	The probability that a healthy individual in quarantine (4) will become infected during the quarantine and she is still in quarantine (but now is already infected) (3) at time t	$\in (0,1)$
$(Pr)_t^{45}$	The probability that a healthy individual in quarantine (4) dies (5)	$\in (0,1)$
*Estimated on empirical data	**E.g. due to contacts with close family members	

Table 3. Variables & Parameters that are computed by the program after each iteration

Variable	Explanation	Restr.
$(Pr)_t^{13}$	The probability that a healthy individual (1) will become treated in the hospital (or isolation) after becoming infected (3) at time t	$\in (0,1)$
$(Pr)_t^{42}$	The probability that a healthy individual in quarantine (4) will become infected at the end of her quarantine ** (2)	$\in (0,1)$
p	Temporal variable (threshold probability 1)	$\in (0,1)$
q	Temporal variable (threshold probability 2)	$\in (0,1)$
r	Temporal variable (threshold probability 3)	$\in (0,1)$
s_t^{Ind}	Health status of the individual at time $t > 0$ (1 - healthy, 2 - infected, 3 - treated, 4 - healthy individual in preventive quarantine, 5 - dead)	Int $\in \{1,2,3,4,5\}$
$(Age)_t^{Ind}$	Age of an individual at time $t > 0$	
$(Wp)_t^{Ind}$	Productivity of an individual at time $t > 0$	$\in \langle 0,1 \rangle$

4. Potential epidemic scenarios

As part of the study, we conducted a number of simulations. We present four most important scenarios that will allow to assess the validity and effectiveness of the restrictions introduced in countries in the face of the development of the COVID-19 pandemic. In the next part of the article, we also present the impact of the pandemic on the economy using the DSGE model for the following four scenarios.

4.1. Scenario 1: The persistent spread of the epidemic under mild restrictions

In the first scenario, we analyze the spread of the coronavirus in the country under mild restrictions, i.e. we assume that people with symptoms of the disease are taken to compulsory home isolation or, in more severe cases, they are hospitalized. In both cases the agents spend there at least three weeks. People who have had contact with an infected person may be quarantined with a given probability. The quarantine period is a minimum of two weeks. At the same time, governments do not decide to adopt additional restrictions.

In order to simulate this scenario, we assume that the model works as presented in the previous section 3. In each scenario, one iteration corresponds to a week. The scenarios are carried out for a period of two years ($T = 104$). In order to speed up the simulation, we adopted 10,000 agents in the model (N^{Ind}) and in the codes available in the external *Comses.net* repository. The results are, however, robust for changing the number of agents all the way up to 1,000,000 and changing the dimensions of the initial grid accordingly ($S_t \times S_t$ for $t = 0$). We assumed that the initial number of infected individuals is equal to 150. The dimensions of initial grid were adopted in a such way to replicate the population density of the country under study. Each individual is characterized by the age. The model also replicates the division of society in terms of pre-productive ($(Ag)_t^1$), productive ($(Ag)_t^2$) and post-productive ($(Ag)_t^3$) ages according to official CSO's statistics. In this scenario, we assume that the average productivity of an individual who is infected is 0.9, while the average productivity of an agent under treatment in hospital or during home isolation is 0.3. At the same time, the average productivity of healthy person in preventive quarantine is 0.8. The adopted values are consistent with the results of estimates found in the literature. The estimates of transition probabilities between states were computed based on data provided by European Centre for Disease Prevention and Control, the Lancet Commission on COVID-19 and national authorities, see Figure 1 & Tables 2, 3 & 4.

Figure 2 presents the spatial-temporal distribution of healthy ($S_t^{Ind} = 1$, (h)), infected ($S_t^{Ind} = 2$, (i)), treated ($S_t^{Ind} = 3$ (l)), quarantined ($S_t^{Ind} = 4$ (k)) and deceased ($S_t^{Ind} = 5$ (d)) agents at $t = 1, t = 8, t = 20$ and $t = 52$ respectively.

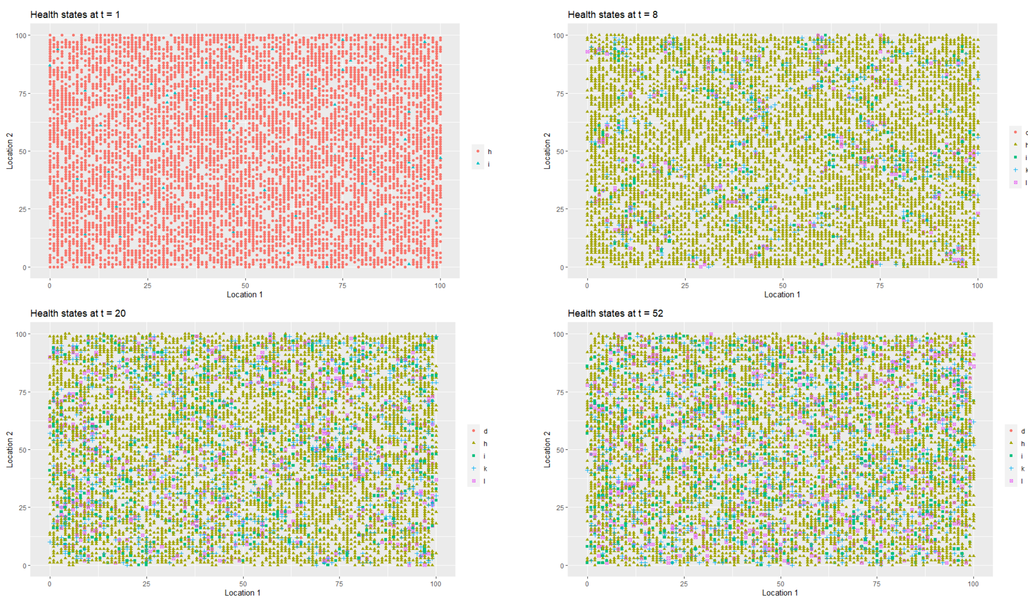

Figure 2. Scenario 1: Spatial-temporal spread of the coronavirus in the society
States: Healthy (h), Infected (i), Treated (l), Preventive quarantine (k), Deceased (d)

Figure 3 presents the changes in agents' labor productivity over time during epidemics under mild restrictions. The disaggregated data is then used to calculate productivity for society (for all t). When interpreting the charts, it is worth remembering that people in pre-productive age and retired have by definition zero productivity. A drop in productivity for a person of working age is possible when the person is infected, under treatment or in quarantine.

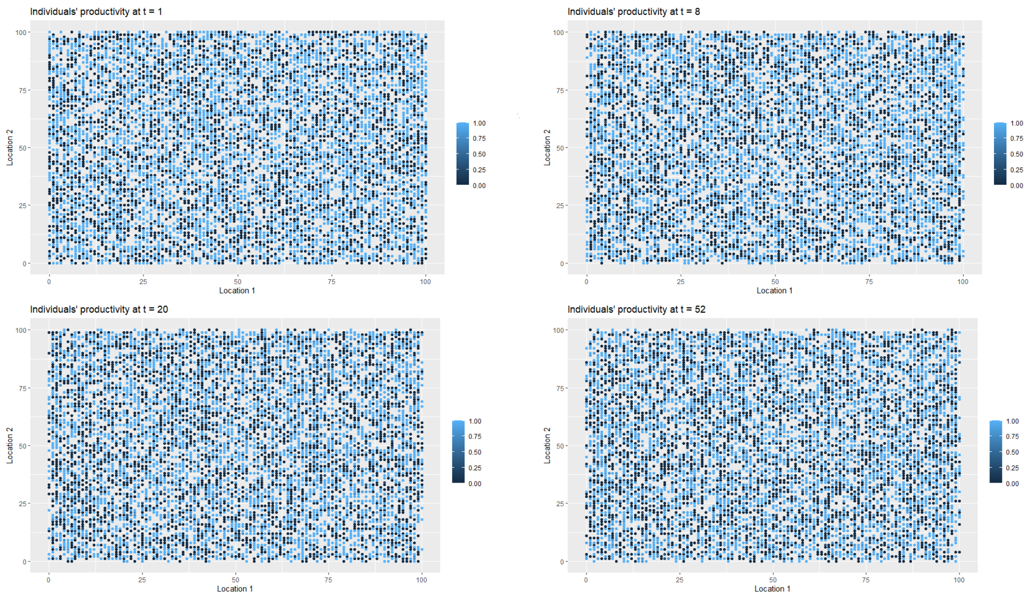

Figure 3. Scenario 1: Changes in agents' productivity over time during epidemics

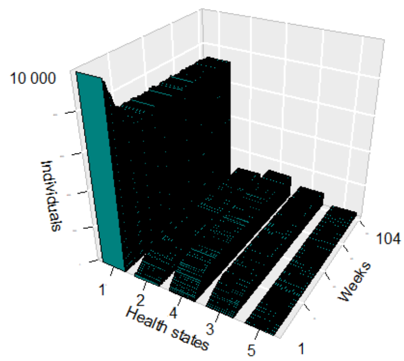

Figure 4. Scenario 1: 3D histogram of health states

Figure 4 presents a 3D histogram showing the change in the number of agents with different health conditions over time. In this scenario, we observe a gradual decrease in the percentage of healthy people. On the other hand, the percentages of people under treatment, quarantined and deceased increase over time. At $t = 8$ 2.79% of population is infected, 2.12% of population is hospitalized or in home isolation, 5.13% of population is healthy, but remains in preventive quarantine, while the mortality rate is marginal and less worrisome (0.02%). After 5 months the percentage of healthy people drops from approximately 98.51% at $t = 1$ to 78.81%, while the percentage of infected increases to 6.19%. The percentage of people in preventive quarantine increases to 9.91%. The percentage of hospitalized agents or those who remains in home isolation increases to 5% of population. After one year, the percentage of healthy individuals drops to 73.34%. The percentage of infected remains high at 7.35% of population at $t = 52$. The percentage of agents in preventive quarantine stabilizes at the level approximately 11.81%, while the percentage of treated at 7.22% of population. The percentage of deceased individuals reaches 0.28% of population. After a year, the values stabilize, while the epidemic continues and the negative effects on the economy are visible and (at least partially) permanent.

Figure 14 shows the changes in labor productivity resulting from the spread of the virus and the adoption of mild restrictions in the form of quarantine. In the first scenario, the productivity stabilizes at approximately 95% of the original value. Thus, a permanent decline in productivity is observed.

Table 4. Comparison of calibration of scenarios 1–4

Notation	Scenario 1	Scenario 2	Scenario 3	Scenario 4
T	104	104	104	104
N^{Ind}	10 000	10 000	10 000	10 000
K^{Ind}	150	150	150	150
$S_t \times S_t$	100×100 for all t	Dynamic adjustment	Dynamic adjustment	100×100 for all t
$(Ag)_t^1$	0.181	0.181	0.181	0.181
$(Ag)_t^2$	0.219	0.219	0.219	0.219
$(Ag)_t^3$	0.6	0.6	0.6	0.6
$(Wp)_t^{av\_h}$	1 for all t	Dynamic adjustment	Dynamic adjustment	1 for all t
$(Wp)_t^{av\_inf}$	0.9	0.9	0.9	0.9
$(Wp)_t^{av\_q}$	0.8	0.8	0.8	–
$(Wp)_t^{av\_t}$	0.3	0.3	0.3	0.3
$(Pr)_t^{12}$	0.03	0.03	Dynamic adjustment	0.2
$(Pr)_t^{13}$	0.1	0.1	Dynamic adjustment	0
$(Pr)_t^{15}$	0.00002	0.00002	Dynamic adjustment	0.00002
$(Pr)_t^{21}$	0.6998	0.6998	Dynamic adjustment	0.6998
$(Pr)_t^{24}$	0.2	0.2	Dynamic adjustment	0.2
$(Pr)_t^{25}$	0.0002	0.0002	Dynamic adjustment	0.005
$(Pr)_t^{41}$	0.6	0.6	Dynamic adjustment	–
$(Pr)_t^{43}$	0.1	0.1	Dynamic adjustment	–
$(Pr)_t^{45}$	0.0002	0.0002	Dynamic adjustment	–
$(Pr)_t^{31}$	0.7	0.7	Dynamic adjustment	0.7
$(Pr)_t^{35}$	0.0002	0.0002	Dynamic adjustment	0.002

4.2. Scenario 2: The spread of epidemic under mobility restrictions

In the second scenario, we analyze the impact of the lockdown on the spread of the virus and on the economy. In this scenario, it is assumed that a very deep lockdown is introduced for a relatively long period of time (at least 2 months).

Lockdown was introduced into the model as a mobility restriction that modifies the grid and interactions in the neighborhood. The grid is dynamically optimized throughout the simulation run. Contrary to the first scenario, in this scenario, the productivity of a healthy agent is not constant and equal to 1. During a lockdown and an open-up phase, the productivity of such an agent is correspondingly lower. The productivity differential reflects the varying degrees of impact of the pandemic on relevant sectors of the economy.

The introduction of a deep lockdown enables the reduction of a long-term decline in productivity in the economy, see Figure 14. It is also the only solution to return to the pre-crisis level of productivity within two years, without the permanent loss of productivity due to an increase in deaths and permanent job destruction (which could also lead to an increase in the unemployment rate due to hysteresis).

As it was the case in first scenario, Figure 5 presents the spatial-temporal spread of the coronavirus in the society, while Figure 6 illustrates data on the changes of agents' labor productivity over time during pandemics.

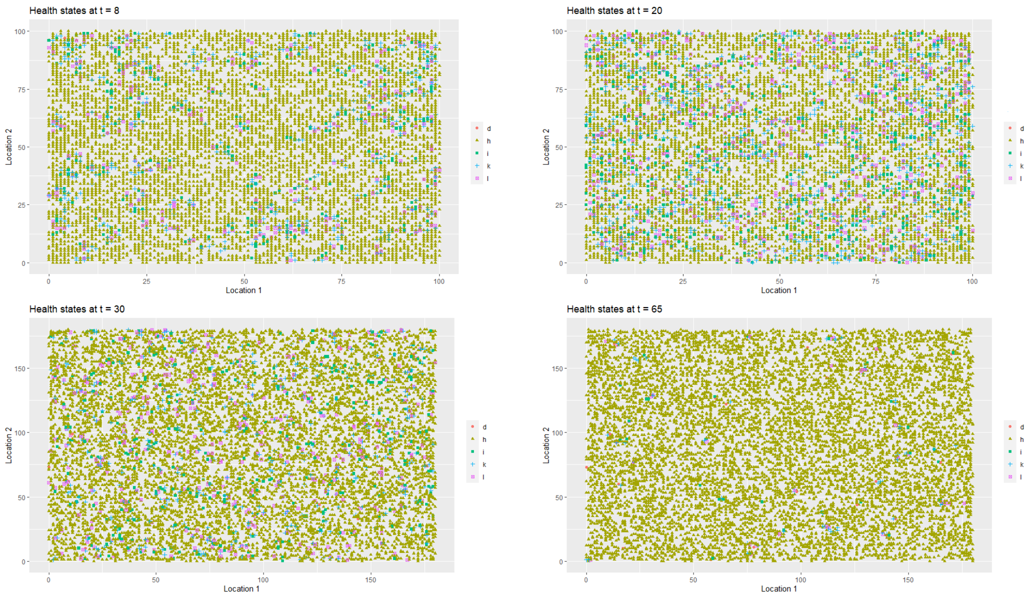

Figure 5. Scenario 2: Spatial-temporal spread of the coronavirus in the society (for first sub-scenario*).
States: Healthy (h), Infected (i), Treated (l), Preventive quarantine (k), Deceased (d)
*See robustness checks in section 6 for further explanation.

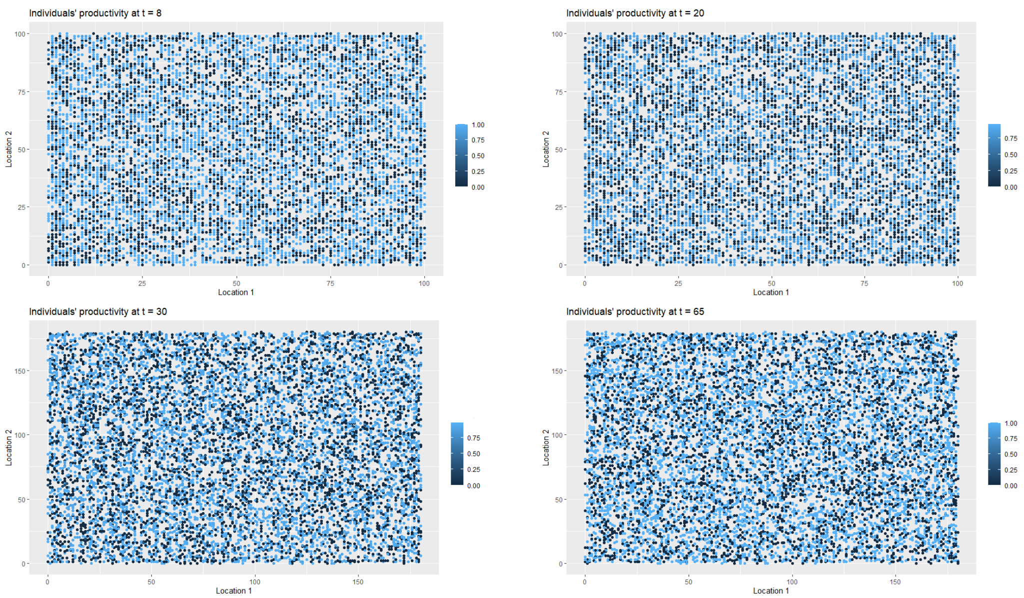

Figure 6. Scenario 2: Changes in individuals' productivity over time during epidemics for first sub-scenario.

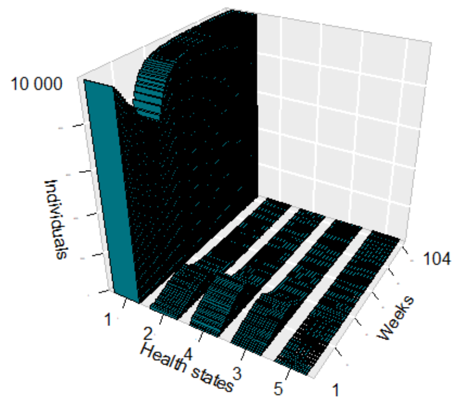

Figure 7. Scenario 2: 3D histogram of health states in the first sub-scenario

Figure 7 presents a 3D histogram showing the change in number of agents with different health status over time. At $t = 8$, the percentage of healthy agents in the society accounts for 89.27%, while the percentage of infected is equal to 2.88%. At the same time, 2.58% of population was hospitalized or remains in home isolation and 5.29% is in preventive quarantine. At $t = 20$, we observe an increase in the number of infected (up to 6.24%) and those taken in preventive quarantine (up to 10.24%). 5.96% of individuals was hospitalized or remains at home isolation and the percentage of deceased increased to 0.06%. Consequently, only 77.27% of the population is in good health. At $t = 30$, 88.06% of population is healthy, while 3.70% is infected. 4.33% is under preventive quarantine and 3.79% under treatment. Approximately 0.12% of population may die. At $t = 65$, the economy and public health return to normality. 98.47% of agents remains healthy, while only 0.36% is infected. A low percentages of subjects are treated (0.33%), quarantined (0.59%) or die (0.25%).

4.3. Scenario 3: The spread of epidemic under gradual preventive restrictions

In the third scenario, we analyze the impact on the spread of the virus and on the economy of introducing gradually preventive restrictions on society and the functioning of the economy. There are different types of restrictions that are included in the scenario. In particular, however, various types of mobility restrictions, restrictions affecting the probability of infection and lockdown should be distinguished.

In the second scenario, we dynamically adjust the grid and the interactions in the neighbourhood (as in the previous scenario), but we also assume that the restrictions may affect the transition probabilities in the model. The labor productivity of healthy workers during the lockdown and open-up phase is also optimized as in the previous case. For details see the code available available in an external repository *Comses.net*.

About two months after the spread of the virus in the country has been identified, preventive measures in the form of mandatory indoor masks and a campaign to promote greater hygiene are carried out, see Figure 14. As a result of the conducted information campaign, the curve showing the new number of cases flattens out temporarily. At the same time, fewer people require hospitalization, fewer people are quarantined and the death rate is also much lower. However, due to the behavioral factor, the period of public compliance with the new restrictions does not last longer than a month. From week 11, agents gradually assess compliance with the restrictions imposed by the regulator more and more negatively, which increases the number of infections and agents put in the preventive quarantine. The increase in the rate of spread of the virus leads to a decrease in the productivity of individual agents and the entire society.

In response to the increase in the number of cases in society, the regulator introduces new restrictions after approximately a month. In response to the distinction between restrictions imposed on individual areas depending on the incidence rate among the inhabitants of a given area, the incidence curve and, consequently, the productivity curve temporarily flatten. The effectiveness of mobility restrictions within individual areas is relatively low. It is mainly related to the relatively high communication of zones, high mobility of the society and the need to provide products within the supply chain. As a consequence, over time, more and more people are infected and more and more zones are covered by new restrictions, which turn out to be relatively ineffective.

Due to the alarming number of infections and the general decline in society's productivity, the regulator's efforts to improve the effectiveness of countermeasures and regulations have been seen. In particular, mobility restrictions are being strengthened, including in particular:

- local lockdown, i.e. for specific areas of the country
- moderate mobility restrictions in public transport
- limiting the number of people participating in assemblies and meetings
- the emphasis is on remote work in selected sectors of the economy, where this remote work does not reduce the overall productivity of the sectors
- hybrid preventive measures in the education sector

Once again, it is worth considering the behavioral factor, i.e. the degree to which the public adapts to the new operating conditions. People are less restrictive over time with the rules and control schemes in place. From the 26th week onwards, this causes a renewed increase in the number of infections (also the number of people in quarantine, treatment and deaths, respectively) and a decrease in the productivity of the society.

Observing the data, it is possible to notice a positive temporary impact on the stabilization of the situation of the measures introduced so far. Therefore, an intensified information campaign is being carried out, along with tougher penalties for not applying them, which brings positive results (at least until disinformation campaigns concerning epidemics in social media and mass media are strengthened).

Along with the growing popularity of disinformation campaigns, the resistance in society to complying with the restrictions is increasing, which is also reflected in protests (protests of companies operating in particularly vulnerable sectors and the anti-COVID-19 movements).

The prolonged epidemiological crisis and the increase in morbidity worsen the situation of the health care system. The problem with the availability of beds and medical equipment in hospitals and the excessive burden on doctors and medical staff is growing successively. In response to the exponential increase in the number of infections (the number of infections per 1,000 inhabitants exceeded the tipping point) and the collapse of the healthcare system, the regulator is introducing a total lockdown in the country.

Lockdown lowers the productivity of all people of working age, including healthy people. The degree of decline in productivity depends on the sector in which the agent is employed. Nevertheless, it allows for a significant reduction in the number of infections and deaths per day. The recovery from lockdown takes place over a longer period of time and is carried out at different rates by different sectors of the economy, hence the increase in productivity in the economy is not sudden and is spread over time.

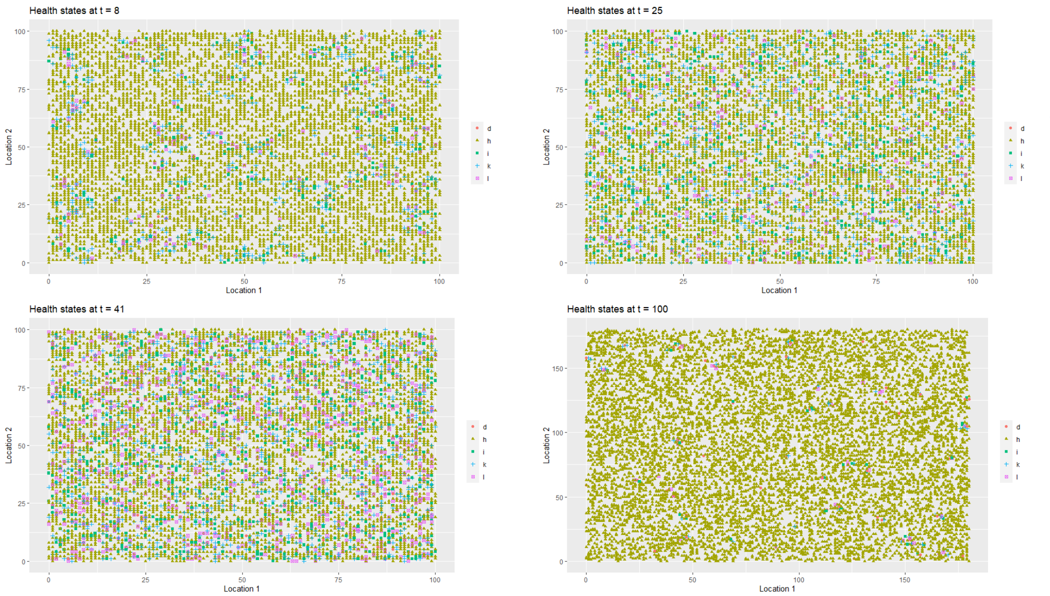

Figure 8. Scenario 3: Spatial-temporal spread of the coronavirus in the society
States: Healthy (h), Infected (i), Treated (l), Preventive quarantine (k), Dead (d)

Figure 8 illustrates the changes in health statuses that result from the introduction of preventive restrictions by the social regulator and appropriate behavioral agents' responses to the restrictions over time. Figure 9 presents data on agents' labor productivity over time during epidemics in the third scenario.

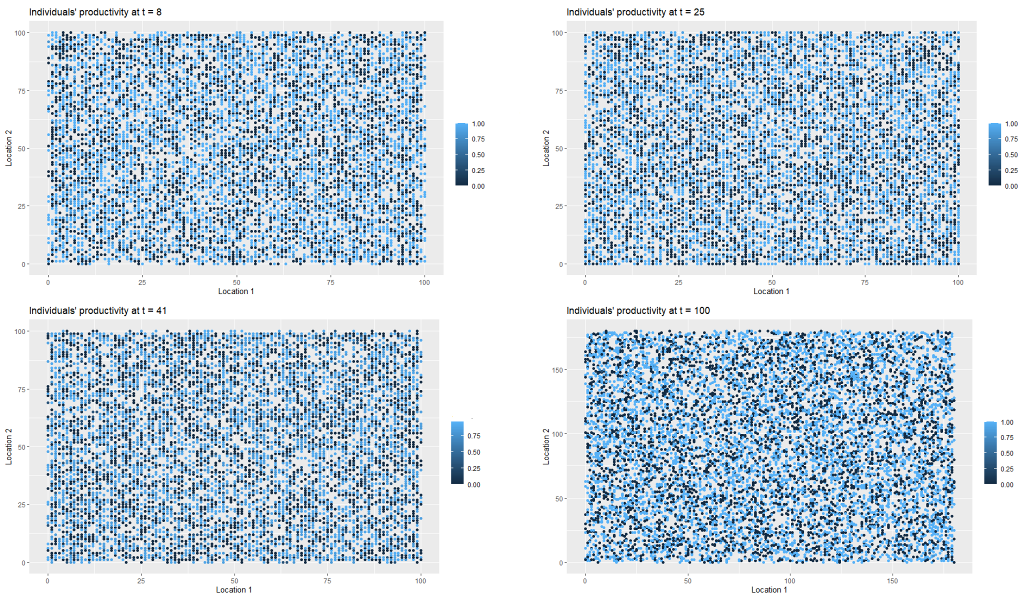

Figure 9. Scenario 3: Changes in individuals' productivity over time during epidemics

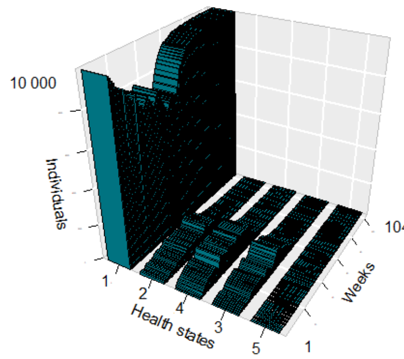

Figure 10. Scenario 3: 3D histogram of health states

Figure 10 presents a 3D histogram showing the change in the number of agents with different health conditions over time. In this third scenario, we observe a successive changes in the percentage of healthy people over two years horizon. At $t = 8$, 89.63% of population is healthy, 2.65% of population is infected, 1.79% of population is hospitalized or in home isolation, 5.9% of population is healthy, but remains in preventive quarantine, while the percentage of deaths in population reaches 0.03%. At $t = 25$, the percentage of healthy individuals decreases to 80.79%. The percentages of infected agents as well as the percentage hospitalized or put in isolation or in preventive quarantine increase (respectively to 5.98%, 2.87%, and 10.18%). The percentage of deceases agents reaches 0.18%. During the lockdown, at $t = 41$, the percentage of healthy individual drops to 71.01%. At the same time, 7.65% of agents are infected and 9.14% are under treatment or home isolation. 11.85% of population is in preventive quarantine. However, applying a lockdown has positive medium-term effects on public health and the economy. At $t = 100$, 98.36% of population is healthy, while only 0.35% infected and 0.34% under treatment. The percentage of deceased agents does not exceed 0.5% of population.

4.4. Scenario 4: The persistent spread of epidemic without restrictions

In the last scenario, we analyze the situation where the coronavirus spreads in the society in a much more aggressive manner and its death rate is also higher. In this scenario, we assume that the regulator has not imposed any restrictions on society. In particular, it deviated from large-scale testing and did not introduce mandatory isolation for diagnosed persons or agents who came into contact with an infected person (preventive quarantine or home isolation). This situation corresponds to highly mobile societies with poor quality or restricted access to healthcare systems.

In this scenario, we modify the basic model in two ways. On the one hand, we assume that the virus is more contagious and may be associated with higher than assumed mortality, e.g. in the absence of an effective health care system or due to mutation. On the other hand, all forms of preventive restrictions and control schemes are excluded from the model. In particular, in this scenario, agents who have been in contact with an infected person do not need to be quarantined.

In Figure 11 we present a dangerous spread of the virus in the society, while in Figure 12 the changes of agents' labor productivity over time. In Figure 13, we present a 3D histogram of health states for the fourth scenario. In this explosive scenario, at $t = 20$ only 62.22% of population is healthy and almost almost a quarter of the population is infected (24.54%). There is no preventive quarantine. 11.07% of population is in the hospital or remains at home in less severe cases. The percentage of deceased exceeds 2% of population. The situation is gradually getting worse. After one year, only 59.46% of population are healthy. 23.07% of agents are infected and 10.36% are hospitalized or stay at home. The mortality rate increases significantly. At $t = 52$, 7.11% of population may die due to infection or comorbidities. If the regulator's remedial measures had not been taken, and the situation continued to worsen the following year, we would have seen alarming data on infected and mortality rates, and a significant decline in labor productivity. At $t = 80$, the percentage of infected agents would stabilize at 22-23% (it would reach 22.51%). However, mainly due to an inefficient health care system, the percentage of hospitalized individuals (or those in home isolation) would not change (10.06%). The death rate could increase up to 11.55%. This actually shows the scale of the problem and the need for active public policy since the beginning of the epidemics.

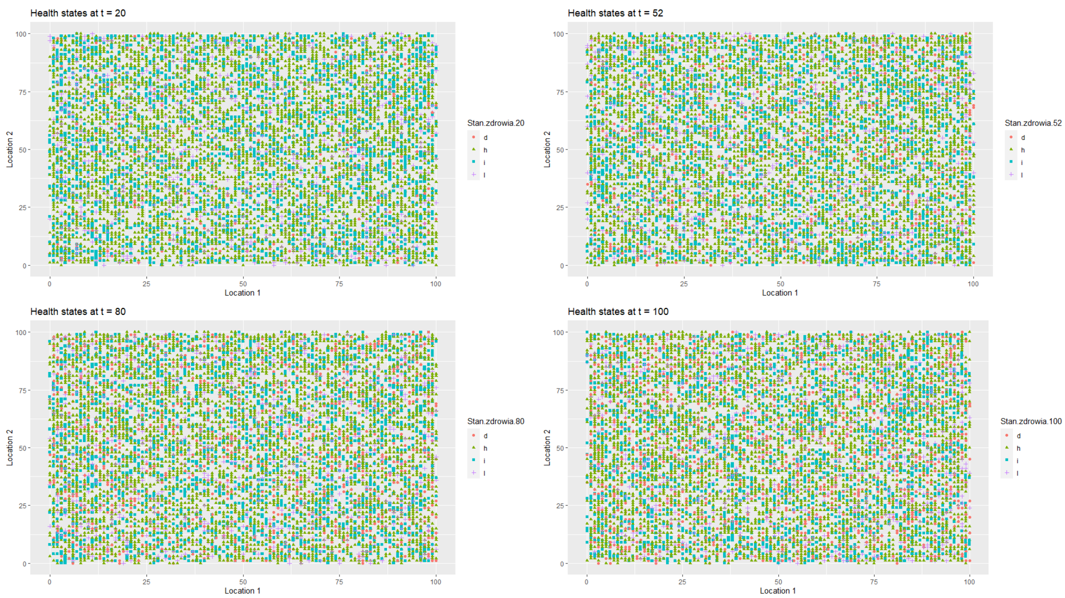

Figure 11. Scenario 1: Spatial-temporal spread of the coronavirus in the society
States: Healthy (h), Infected (i), Treated (l), Preventive quarantine (k), Deceased (d)

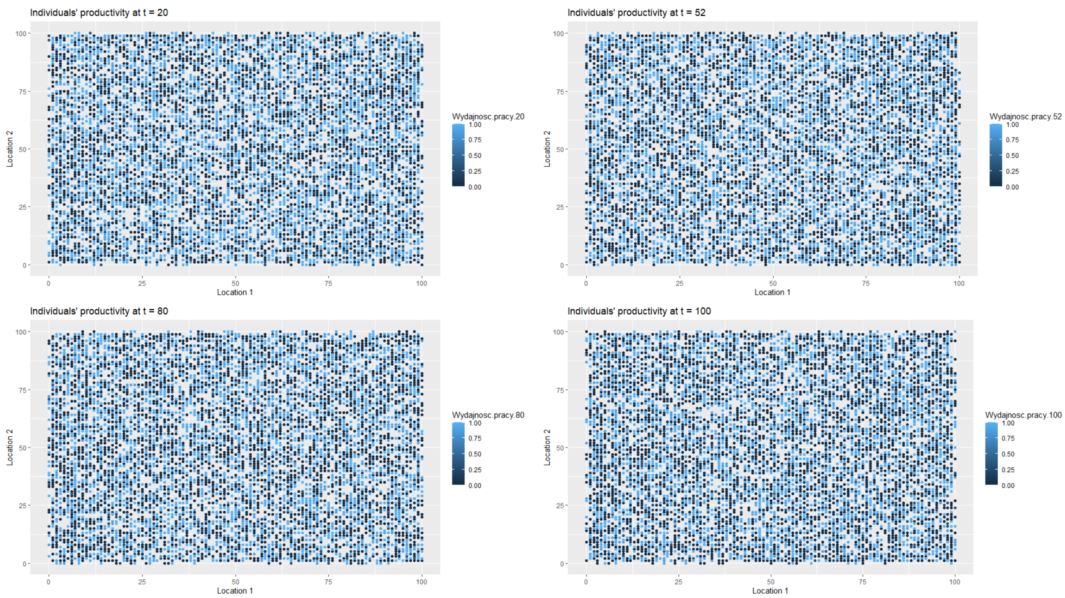

Figure 12. Scenario 4: Changes in individuals' productivity over time during epidemics

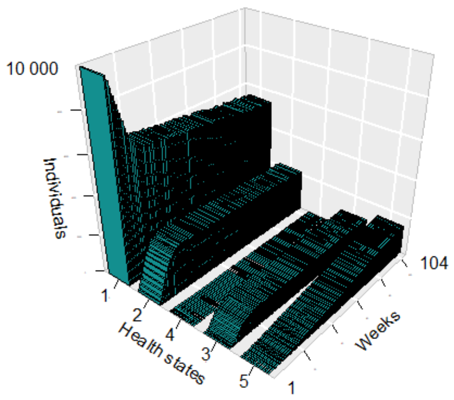

Figure 13. Scenario 4: 3D histogram of health states

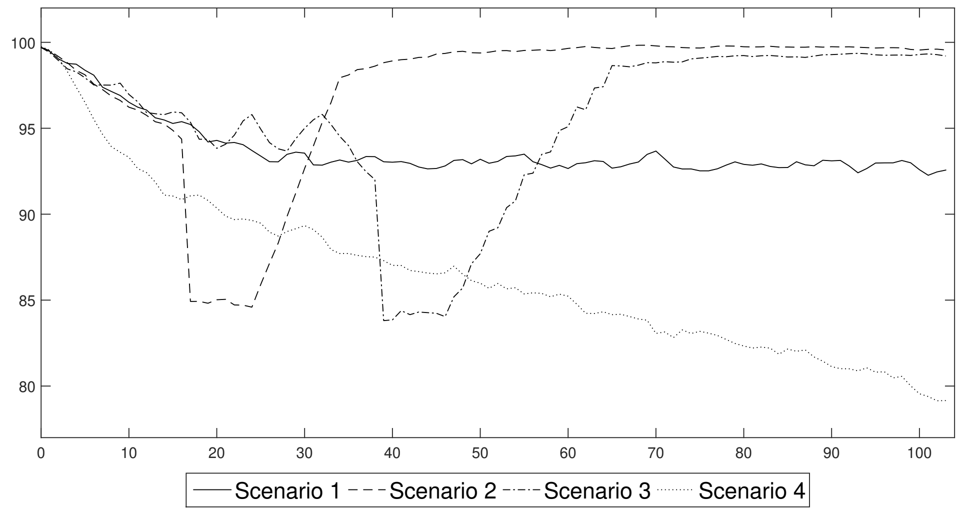

Figure 14. Aggregate labour productivity under different COVID-19 prevention and control schemes

408 In Figure 14, we observe a permanent decline in productivity in the economy as a result of the increase in agent mortality. When the tipping point of an epidemic is exceeded, crisis management becomes extremely difficult. An increasing percentage of the population, including those of working age, is infected. This leads to downtime in companies and ineffective staff turnover, with the result that the more productive and highly skilled sectors suffer mainly. Initially, the exponential trend slows down gradually. From $t = 47$ we observe a practically linear decline in productivity, which is the result of the gradual (though very slow) development of herd immunity by society. However, the further decline in productivity is long-lasting, as we assume that entities acquire only temporary immunity, which is confirmed by the latest research on the coronavirus.

5. Macroeconomic consequences of pandemics - DSGE approach

In order to assess the macroeconomic consequences of COVID-19 epidemic under different prevention and control schemes, we construct a DSGE model, which accounts for the most important business cycle characteristics of modern economies. To keep our considerations relatively simple we adapt the basic model proposed by Gali [25] and extend it through an introduction of capital accumulation component defined in a way which draws heavily from the work of Christiano et al. [26] as well as the labour market component developed along the lines of Gali [27,28] and Gali et al. [29]. In order to make it possible for the model to account for the impact of COVID-19 epidemic on the analysed economic system, we do propose an introduction of an additional shock, which affects the productivity of labour. Such an approach enables us to model the falls in the availability of employees related to the process of COVID-19 widespread and resulting economic disturbances. Below we present and discuss the most important characteristics of the macroeconomic model used in our further analyses and its calibration.

The model assumes that an economy is populated by a unit mass *continuum* of households which maximise their utility levels by solving the following optimisation problem:

$$\max E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[U\left(C_t, N_t\right) \right] \right\}, \tag{1}$$

where: E_0 is a rational expectations operator representing information possessed by a household in period 0; β is a discount factor such that $\beta \in [0;1]$; C_t is the value of a household's total consumption in period t; N_t is the amount of labour provided by a household in period t; $U\left(C_t, N_t\right)$ is a twice differentiable, instantaneous utility function and $\frac{\partial U(C_t,N_t)}{\partial C_t} > 0$, $\frac{\partial^2 U(C_t,N_t)}{\partial^2 C_t} \leq 0$ and $\frac{\partial U(C_t,N_t)}{\partial N_t} > 0$, $\frac{\partial^2 U(C_t,N_t)}{\partial^2 N_t} \leq 0$ represent diminishing marginal utilities of consumption and labour. The utility function is of King et al. [30] type, namely: $U\left(C_t, N_t\right) = \ln \tilde{C}_t - \epsilon_t^{\chi} \frac{N_t^{1+\varphi}}{1+\varphi}$, where ϵ_t^{χ} is an exogenous preference shifter representing the impact of a labour supply shock governed by the AR(1) process of the form: $\ln \epsilon_t^{\chi} = \rho_{\chi} \ln \epsilon_{t-1}^{\chi} + \xi_t^{\chi}$, $\xi_t^{\chi} \sim i.i.d.N(0, \sigma_{\chi}^2)$, $\rho_{\chi} \in [0;1]$ and $\varphi > 0$ is the inverse of the Frisch elasticity of labour supply. Following the empirical models of Christiano et al. [26], Smets and Wouters [31] and Gali et al. [29] and more fundamentally the seminal paper by Abel [32], it is assumed that households' consumption is characterised by habit persistence determined by external habit formation of the form: $\tilde{C}_t \equiv C_t - hC_{t-1}$, where $h \in [0, 1]$ is the habit persistence parameter and C_{t-1} is the value of lagged aggregate consumption.

Households' income comes from work (its differentiated types are indexed with i) and lump-sum transfers. It is used in order to finance current consumption involving the purchase of diversified goods produced by companies (with types indexed with z) or postpone consumption and buy one-period risk-free government bonds (the so-called *Arrow securities*). In order to make our DSGE model closer to standard economic representations of the production process, we do also include capital into our considerations. The physical stock of capital is owned and maintained by the households who rent its services to the companies. The capital market is perfectly competitive and the nominal capital rental rate is given by R_t^k. Following the discussion in Christiano et al. [26] and Christiano et al. [33], capital accumulation process is represented by equation:

$$K_{t+1} = \left[1 - \frac{\phi_k}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] I_t + (1-\delta)K_t. \tag{2}$$

where: $\phi_k > 0$ is the capital adjustments costs' scaling parameter and $\delta \in (0;1)$ is the capital depreciation rate.

The intertemporal budget constraint of a household which equates income with spending is written as:

$$\int_0^1 C_t(z)P_t(z)dz + I_t + Q_tB_t \leq B_{t-1} + \int_0^1 W_t(i)N_t(i)di + R_t^kK_t + Div_t - T_t \quad (3)$$

where: $C_t(z)$ and $P_t(z)$ denote respectively consumption and price of z-th type goods, $C_t = \left(\int_0^1 C_t(z)^{\frac{\varepsilon_C-1}{\varepsilon_C}}dz\right)^{\frac{\varepsilon_C}{1-\varepsilon_C}}$; $N_t(i)$ and $W_t(i)$ are the i-th type labour wage level in period t; $\varepsilon_c \geq 1$ describes the elasticity of substitution between different types of goods; Q_t denotes the price of the Arrow securities; B_t is the number of risk-free government bonds purchased at a discount by a household in period t; Div_t is the value of all dividends received by households from companies; and T_t is the net value of all lump-sum taxes paid and transfers received by a representative household.

Solving the households' optimisation problem requires tackling the problem of optimal allocation of expenditures among different types of goods, which results in: $C_t(z) = \left[\frac{P_t(z)}{P_t}\right]^{-\varepsilon_c} C_t$, $\int_0^1 P_t(z)C_t(z)dz = P_tC_t$, $P_t = \left(\int_0^1 P_t(z)^{1-\varepsilon_c}dz\right)^{\frac{1}{1-\varepsilon_c}}$ and in the transversality condition given by: $\lim_{T\to\infty} \beta^T E_t\{\frac{B_T}{C_T}\} \geq 0$.

The model accounts for the existence of wage rigidities. It is assumed that households provide differentiated labour services (indexed by i) and the level of wages is determined by trade unions which specialise in supplying only a given type of labour. Each of the unions is an effective monopolist as the supplier of a given type of labour. Because of their position, they can demand wage rates exceeding the marginal rate of substitution between consumption and leisure by a mark-up indicative of their market power. The renegotiation of employment contracts with entrepreneurs is costly and subjected to some restrictions, similar to those introduced by the Calvo [34] pricing scheme. Namely, only the exogenously determined, randomly selected group of trade unions given by $1-\theta_w$, where $\theta_w \in [0;1]$, can re-optimise wages in a given period by choosing W_t^*. The group is big enough for its decisions to influence the aggregate nominal wage rate given by W_t. When deciding about the level of wages, trade unions consider consumption choices of households supplying a given type of labour and take the maximisation of the households' utility as their ultimate goal. Assuming that all households are identical leads to the following symmetrical problem:

$$\max_{W_t^*} E_t \left\{ \sum_{k=0}^{\infty} (\beta\theta_w)^k U\left(C_{t+k|t}, N_{t+k|t}\right) \right\}, \quad (4)$$

$$N_{t+k|t} = \left(\frac{W_t^*}{W_{t+k}}\right)^{-\varepsilon_w} \int_0^1 N_t(z)dz, \quad (5)$$

$$P_{t+k}C_{t+k|t} + I_{t+k|t} + Q_{t+k}B_{t+k|t} \leq B_{t+k-1|t} + W_{t+k}N_{t+k|t} + R_{t+k}^kK_{t+k|t} + Div_{t+k} - T_{t+k}, \quad (6)$$

where $C_{t+k|t}, W_{t+k|t}^*, B_{t+k|t}, I_{t+k|t}, K_{t+k|t}$ denote, respectively, the level of consumption, nominal wages, risk-free government bonds, investments and capital selected by a household or a trade union that re-optimises wages in period t and keeps them unchanged up to and including period $t+k$. The FOC of the trade union's optimisation problem is given by:

$$\sum_{k=0}^{\infty} (\beta\theta_w)^k E_t \left\{ N_{t+k|t}U\left(C_{t+k|t}, N_{t+k|t}\right) \left[\frac{W_t^*}{P_{t+k}} - \frac{\varepsilon_w}{\varepsilon_w - 1} MRS_{t+k|t}\right] \right\} = 0, \quad (7)$$

where $MRS_{t+k|t} = -\frac{U_N(C_{t+k|t}, N_{t+k|t})}{U_C(C_{t+k|t}, N_{t+k|t})}$ is the marginal rate of substitution of households/labour unions that selected a nominal wage level in period t and kept it unchanged up to and including period $t+k$. The average wage level in this case is given by: $W_t = \left[\theta_w(W_{t-1})^{1-\varepsilon_w} + (1-\theta_w)^{1-\varepsilon_w}\right]^{\frac{1}{1-\varepsilon_w}}$.

As well as choosing the optimal wage level, households also make decisions about labour supply. The decisions are crucial from the perspective of the unemployment component because unemployment is determined by comparing labour supply and labour demand arising from firms' production needs. That part of the model is developed according to the framework proposed by Gali

[27]. It assumes that each of the infinitely many households indexed by $g \in [0;1]$ has an unlimited number of members given by a *continuum* of size one [35]. Household members provide diversified labour services involving specific levels of disutility given by $\epsilon_t^X j^\varphi$, where $\epsilon_t^X > 0$ is an exogenous labour supply shock that affects all household members in exactly the same way, $\varphi > 0$ denotes the elasticity of marginal disutility from labour between household members, and j stands for disutility from labour normalized so that $j \in [0,1]$. Therefore, the economy has infinitely many units defined in the $g \times i \times j$ space with dimensions of $[0,1] \times [0,1] \times [0,1]$ and indexed by vector (g,i,j).

Labour market participation decisions are taken individually by household members with a view to maximizing household's utility from consumption and leisure. In considering whether or not to work, household members take account of households' choices concerning the optimal level of consumption and trade unions' decisions about the level of real wages. In other words, they treat the values of all variables other than labour supply as given and assume that all job seekers will find employment. Therefore, they need to solve the following optimisation problem:

$$\max E_{L_t(g,i,j)} \left\{ \sum_{t=0}^{\infty} \beta^t \left[U\left(C_t, \epsilon_t^X j^\varphi L_t(g,i,j)\right)\right] \right\}, \tag{8}$$

$$P_t C_t + Q_t B_t + I_t \leq B_{t-1} + W_t(i) L_t(g,i,j) + R_t^k K_t + Div_t - T_t. \tag{9}$$

where $L_t(g,i,j)$ is a dummy variable taking the value of 0 when an individual chooses not to work and 1 if they enter the labour market.

From the FOC of the optimisation problem defined in equations 8 and 9 it follows that individuals will be interested in entering the labour market as long as $\frac{W_t(i)}{P_t} \geq \frac{\epsilon_t^X j^\varphi}{U_{C,t}}$, which means that the marginal income from work is greater than its marginal disutility expressed by units of consumption. If disutility from work is ordinal and its increments between individuals doing the same type of work are constant, meaning that the increments are evenly distributed over the $j \in [0;1]$ interval, then it is the disutility of the marginal employee doing a given type of work that determines the rate of economic activity and, consequently, the size of labour supply in the analysed model, $L_t(i)$. Because of the previous assumptions about the homogeneity of households and indivisibility of labour, the above problem is symmetrical and its solution for the aggregate level is the same as that obtained by aggregating the results for individual units and households. This allows the aggregate labour supply equation to take the form of:

$$\frac{W_t}{P_t} = \epsilon_t^X \tilde{C}_t L_t^\varphi, \tag{10}$$

where: $W_t \equiv \left(\int_0^1 W_t(i)^{1-\varepsilon_w} di\right)^{\frac{1}{1-\varepsilon_w}}$ and $L_t \equiv \int_0^1 L_t(i) di$.

In keeping with Gali [27,28] or Gali et al. [29], we assume that the unemployment rate (UR_t) is equivalent to the share of unemployed (understood as the excess of labour supply over demand, $U_t \equiv L_t - N_t$) in the aggregate labour supply. After simple transformations, we have:

$$UR_t \equiv \frac{L_t - N_t}{L_t} = 1 - \frac{N_t}{L_t}. \tag{11}$$

By combining the aggregate labour supply condition from equation 10 with the definitions of the marginal rate of substitution and actual wage mark-up ($\mathcal{M}_{w,t}$), we get:

$$UR_t = 1 - \mathcal{M}_{w,t}^{-\frac{1}{\varphi}}. \tag{12}$$

The framework allows us to obtain a simple relationship which associates the development of unemployment rate with changes in the level of wage markup. The bigger the actual mark-up over the perfectly competitive wage, the higher the unemployment rate.

The model assumes that the economy under consideration has a unit mass *continuum* of firms that produce different categories of goods, with both firms and goods being indexed by $z \in [0;1]$. To produce output Y_t, firms use identical technology described by the standard Cobb-Douglas production function:

$$Y_t(z) = A_t K_t(z)^{\mathcal{A}} \left[\epsilon_t^N N_t(z)\right]^{1-\mathcal{A}} \tag{13}$$

where: A_t is a technological shock of the form: $\ln A_t = \ln \epsilon_t^a = \rho_a \ln \epsilon_{t-1}^a + \xi_t^a$, $\xi_t^a \sim i.i.d.N(0;\sigma_a^2)$, $\rho_a \in [0;1]$; $\mathcal{A} \in [0;1]$. In order to account for the impact of COVID-19 spread on an economy we endow the production function of the model with the labour productivity shock which affects uniformly all of the companies. The shock takes the form of: $\ln \epsilon_t^N = \rho_N \ln \epsilon_{t-1}^N + \xi_t^N$, $\xi_t^N \sim i.i.d.N(0;\sigma_N^2)$, $\rho_N \in [0;1]$. We believe that, it is justified to treat COVID-19-induced disturbances as a transitional random shock, as from the point of view of a company, their occurrence results in a sudden and unpredictable change of economic conditions for which firms can only react with considerable lag. In the majority of cases it does not make any difference whether these disturbances are incurred by the development of the epidemic itself or as a result of introduction of state-operated prevention and control schemes, as the dynamics of the epidemic and the speed with which the decisions are taken leaves only a small margin for reaction. On the other hand, due to relatively low mortality of people in the working age it does not affect the economic conditions in the long run considerably and finally vanishes. Proposed specification which treats the COVID-19-related shock as a labour productivity shock enables us to envisage the consequences of a change in the availability of employees due to their sickness, hospitalisation, quarantining or domestic isolation, as well as due to introduction of remote work organisation, which might either prevent them from working at all or significantly reduce their individual efficiency. It should be noted that in each of these cases employees do not provide fully valuable work, while still working for a given company and being remunerated on a fairly standard basis. As such the COVID-19 shock should not be considered a labour supply shock, which pushes part of the labour force into inactivity, but rather the labour productivity shock, which makes some of the employees unproductive or not fully productive, while keeping them within a formal employment relationship.

It is further assumed that firms choose prices of goods according to the Calvo [34] formalism. In a given period, they can be re-optimised only by a randomly determined group of firms proportional to $1-\theta_p$ (where $\theta_p \in [0;1]$). As a result, θ_p becomes a natural index of price rigidity. Each company re-optimising prices maximises its profit over the predicted period of price validity given by $\frac{1}{1-\theta_p}$. Therefore, firms need to solve the following problem:

$$\max_{P_t^*} \sum_{k=0}^{\infty} \theta_p^k E_t \left\{ \Lambda_{t,t+k} \left[P_t^* Y_{t+k|t} - \Psi_{t+k}\left(Y_{t+k|t}\right)\right]\right\} \tag{14}$$

subject to:

$$Y_{t+k|t} = \left[\frac{P_t^*}{P_t}\right]^{-\varepsilon_c} Y_{t+k} \tag{15}$$

where: $Y_{t+k|t} \geq C_{t+k|t} + I_{t+k|t}$; $Y_{t+k|t}, C_{t+k|t}, I_{t+k|t}$ denote, respectively, the amount of output supplied, consumption to be met and investments introduced by a company re-optimising prices in period t and keeping them unchanged up to and including period $t+k$; P_t^* is the price chosen by companies that re-optimise prices in period t; $\Psi_t(Y_{t+k|t})$ is the nominal marginal cost of a company that re-optimises prices in period t and keeps them unchanged up to and including period $t+k$; and $\Lambda_{t,t+k} = \beta^k E_t \left\{\frac{C_t P_t}{C_{t+k} P_{t+k}}\right\}$. Because all companies that re-optimise prices in a given period take the same decision, the optimisation problem is symmetrical and easy to solve. The aggregate price level is given then by: $P_t = \left[\theta_p P_{t-1}^{1-\varepsilon_c} + (1-\theta_p) P_t^{*\,1-\varepsilon_c}\right]^{\frac{1}{1-\varepsilon_c}}$.

Household members provide firms with diversified labour services indexed by $i \in [0;1]$. In such a case firm's demand for labour might be expressed using the *Armington's aggregator* (Armington 36, Appendix 1 and 2; also known as *Dixit-Stiglitz's aggregator*) given by:

$$N_t(z) = \left(\int_0^1 N_t(i,z)^{\frac{\varepsilon_w - 1}{\varepsilon_w}} di \right)^{\frac{\varepsilon_w}{\varepsilon_w - 1}}, \forall\ i,z \in [0,1]. \tag{16}$$

The level of employment in firms is assessed using a two-stage budgeting procedure [37,38] with which the optimal allocation of expenditures to different types of labour can be defined for every allowable level of costs, and then a firm's total demand for labour, conditionally on the previous solution. Consequently, the following labour demand schedule is obtained:

$$N_t(i,z) = \left[\frac{W_t(i)}{W_t} \right]^{-\varepsilon_w}, \forall\ i,z \in [0;1], \tag{17}$$

where $W_t(i)$ is the real wage amount paid for the i-th type of labour and $W_t = \left[\int_0^1 W_t(i)^{1-\varepsilon_w} di \right]^{\frac{1}{1-\varepsilon_w}}$ represents the aggregate wage level in the economy. Based on the functions presented above, we also get the expression: $\int_0^1 W_t(i) N_t(i,z) di = W_t N_t(z)$.

The proposed model becomes complete with the introduction of additional market clearing conditions. The clearing of the goods market requires that $Y_t(z) = C_t(z) + I_t(z)$. Knowing that $Y_t = \left(\int_0^1 Y_t(z)^{\frac{\varepsilon_C - 1}{\varepsilon_C}} dz \right)^{\frac{\varepsilon_C}{1-\varepsilon_C}}$ and $I_t = \int_0^1 I_t(z) dz$ we can easily show that $Y_t = C_t + I_t$. When prices are sticky, the labour market is cleared at a lower level of employment than if they were perfectly elastic. The labour market clearing is described by the following equation:

$$N_t = \int_0^1 \int_0^1 N_t(z,i)\, \mathrm{d}i\, \mathrm{d}z = \int_0^1 N_t(z) \int_0^1 \frac{N_t(z,i)}{N_t(z)}\, \mathrm{d}i\, \mathrm{d}z. \tag{18}$$

Using the appropriate labour demand functions and the expression for the production function of an individual firm, we obtain:

$$\begin{aligned} N_t &= \int_0^1 N_t(z) \int_0^1 \left[\frac{W_t(i)}{W_t} \right]^{-\varepsilon_w} \mathrm{d}i\, \mathrm{d}z = \Delta_{w,t} \int_0^1 N_t(z)\, \mathrm{d}z = \Delta_{w,t} \int_0^1 \epsilon_t^N \left(\frac{Y_t(z)}{A_t K_t(z)^{\mathcal{A}}} \right)^{\frac{1}{1-\mathcal{A}}} \mathrm{d}z = \\ &= \Delta_{w,t} \int_0^1 \epsilon_t^N \left(\frac{\left[\frac{P_{H,t}(z)}{P_{H,t}} \right]^{-\varepsilon_C} Y_t}{A_t K_t^{\mathcal{A}}} \right)^{\frac{1}{1-\mathcal{A}}} \mathrm{d}z = \Delta_{w,t} \Delta_{p,t} \epsilon_t^N \left(\frac{Y_t}{A_t K_t^{\mathcal{A}}} \right)^{\frac{1}{1-\mathcal{A}}}, \end{aligned} \tag{19}$$

where: $K_t^{\mathcal{A}} = \int_0^1 K_t(z)^{\mathcal{A}}\, \mathrm{d}z$; $\Delta_{p,t} = \int_0^1 \left[\frac{P_{H,t}(z)}{P_{H,t}} \right]^{-\frac{\varepsilon_C}{1-\mathcal{A}}} \mathrm{d}z$ is the measure of domestic price dispersion and $\Delta_{w,t} = \int_0^1 \left[\frac{W_t(i)}{W_t} \right]^{-\varepsilon_w} \mathrm{d}i$ is the measure of wage dispersion. It follows easily from equation 19 that the aggregate production function is given by

$$Y_t = \frac{A_t K_t^{\mathcal{A}} (\epsilon_t^N N_t)^{1-\mathcal{A}}}{(\Delta_{p,t} \Delta_{w,t})^{1-\mathcal{A}}}, \tag{20}$$

whereas the real marginal cost can be specified as

$$RMC_t = \frac{\partial RTC_t}{\partial Y_t} = \frac{W_t}{P_t} \frac{(\Delta_{p,t} \Delta_{w,t})^{1-\mathcal{A}} (\epsilon_t^N N_t)^{\mathcal{A}}}{(1-\mathcal{A}) A_t K_t^{\mathcal{A}}}. \tag{21}$$

In order to close the model, we need one additional equation explaining the specification of the nominal interest rate, which is called a monetary policy rule. It is usually assumed that monetary authorities adopt a policy aimed to prevent prices and output from deviating too much from the steady-state values, which can be described using the following Taylor-type rule:

$$\frac{R_t}{R} = \Pi_t^{p\,\phi_\pi} \left(\frac{Y_t}{Y}\right)^{\phi_y} e^{\epsilon_t^M} \tag{22}$$

where R_t is the nominal interest rate; $\Pi_t^p = \frac{P_t}{P_{t-1}}$ is the inflation rate; ϕ_π and ϕ_y are parameters describing the monetary authorities' reaction to price and output deviations from their steady state values, and $\epsilon_t^M = \rho_M \epsilon_{t-1}^M + \xi_t^M$, $\xi_t^M \sim i.i.d.N(0;\sigma_M^2)$, $\rho_M \in [0;1]$ is a monetary policy shock.

The full set of the equilibrium conditions of the DSGE model is obtained by combining and transforming equations obtained as solutions to the aforementioned optimisation problems. The model is expressed in weekly terms and calibrated so that it matches standard stylised facts concerning the business cycle characteristics of developed economies. As a result we obtain the model, which successfully reproduces results of existing empirical research, such as e.g. an estimated model of Christiano et al. [39]. As the model is expressed in weekly terms, which is necessary in order to reproduce the pace and timing of the COVID-19 epidemic, while very rare in DSGE research, the actual values used in the calibration might arouse some reflection. In what follows, we assume the discount factor $\beta = 0.9996$, which results in the steady-state interest rate taking the level of 2.1% in annual terms. Following Christiano et al. [39] and Gali [28] we set the expected duration of prices and wages to 52 weeks, i.e. 4 quarters, which makes $\theta_p = \theta_w = 0.9807$. Similarly as in Gali [28], we assume that $\epsilon_w = 4.52$ and $\varphi = 5$. As a result steady-state unemployment rate (which in case of the analysed model might be under certain restrictions identified with the natural unemployment rate) takes the value of 4.8%. The habit persistence parameter, h is set at a relatively high level of 0.9, however it seems acceptable if we take into account the fact that the model is expressed in weekly terms. We should expect that consumption is characterised by relatively high week-to-week inertia. Capital share in production given by α is taken at the level of 0.25. In order to obtain appropriate reactions of capital and investment to the changes of economic conditions we assume that $\phi_k = 8$, which is relatively close to the assesments provided by Christiano et al. [39], and $\delta = 0.05$, which is the level that enables identification of the model. The parameters of the Taylor rule are taken at the level of: $\phi_\pi = 0.115$ and $\phi_y = 0.0096$, which enables us to obtain a rule which is consistent with the traditional version of the rule that takes the values of respectively: 1.5 and 0.125 in quarterly terms. Finally, the autoregressive parameters of the shocks are chosen so as to obtain the satisfactory duration of shocks in weekly terms. As a result, we assume: $\rho_a = \rho_\chi = \rho_N = 0.99$ and $\rho_M = 0.965$. Proposed calibration ensures the identification of the model and fulfills the Blanchard-Kahn conditions. The model is expressed and solved in non-linear terms, i.e. we do not log-linearise it around the steady state.

6. COVID-19 prevention and control schemes - efficiency comparison

In this part of the paper we use the labour productivity paths (Figure 14) generated from the agent based epidemic component of Section 3 in order to obtain conditional forecasts of standard macroeconomic indicators: output, capital, investments and unemployment rate. The forecasts come from the DSGE model described in Section 5. Its calibration uses standard values characteristic of a developed economy. The analyses are based on four scenarios which introduce different prevention and control schemes (as introduced in Section 4). All of the results are expressed as a relative difference from the steady state value. The analyses are performed within a two year horizon, which is the minimum that is needed in order to produce a vaccine or establish an efficient cure for the virus. Presented results constitute the mean out of 10000 simulations of the model. Our discussion concludes with a brief analysis of robustness of the obtained estimates.

The results of performed forecasts are presented in Figure 15. Their analysis shows that scenarios might be easily divided into two groups, which produce similar economic trends. The first of them consists of Scenarios 1 and 4, which result in occurrence of negative economic trends that persist in an economy in the medium or even long run. The other group is composed of Scenarios 2 and 3. In that case the economic distortions are relatively short-lived, but their amplitude is bigger.

The first of the groups that were named above consist of the scenarios which assume that the government allows for persistent spread of the disease introducing only general sanitary restrictions that are willingly undertaken and obeyed by the society (Scenario 1) or not introducing any restrictions at all hoping that the propagation of a virus will finally cease out at some point (Scenario 4). Both of these approaches result in relatively high share of people who are either infected or undergoing quarantine, which translates into persistent fall of productivity of labour, which stabilises at the level of approximately 92% of the full capacity or, in the case of unconstrained spread scenario, exhibits a continuous downward trend reaching the level of 80% within the two years from the start of an epidemic. This behaviour of labour productivity translates onto the way in which other variables respond to the shock. In case of Scenario 1 output falls down by at least 2.5% and towards the end of the sample stabilises at the level of the 98% of its steady state value. Also capital and investments exhibit permanent fall of approximately 10%. The unemployment rate goes up by 6 pp. in the first year of the epidemic and stabilises at the level of 5 pp. above the steady state further on. This means that the actual unemployment rate reaches the level of approximately 9%. Within Scenario 4 the changes are much deeper. Output falls initially by approximately 4%, however after a short stabilisation it continues a downward trend and reaches the level of approximately 94% of an initial capacity. Capital falls down together with investments as a persistent fall of output discourages enterprises from undertaking development activities. Unemployment rate goes up and increases by as much as 15 pp. within the first two years of the epidemic. This produces high social cost, as the actual unemployment rate reaches the level of 20%. The costs of Scenario 4 named above do only include its short and medium run consequences leaving aside potential long run loss of human capital resulting from a high death toll. Inclusion of the long run consequences into our assessment would, however, result in the deterioration of an overall balance, which proves that a strategy of no reaction should not be taken as a viable alternative by the government. Also the solution of Scenario 1, however tempting it might be, turns out to be extremely hard to be implemented in practice. Only few countries worldwide successfully curtailed the levels of COVID-19 infections solely to the use of general sanitary restrictions. In the majority of countries societies found it extremely hard to reduce the amount of social contacts and isolate from families and friends.

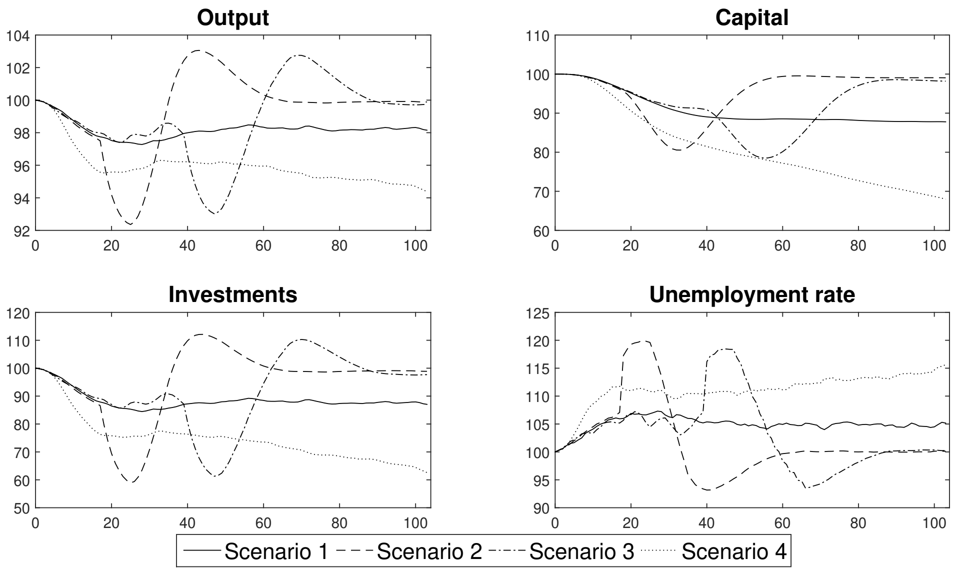

Figure 15. Conditional forecasts of major macroeconomic indicators under different COVID-19 prevention and control schemes

When it comes to the assessment of efficiency of the second group of measures that might be introduced in order to limit the transition of a virus, which consist of different lockdown schemes, we might easily observe that, if applied with an appropriate strength they should be capable of stabilising the number of infections. In our baseline scenario we assume that a lockdown consists of a decrease of professional activity by an average of 15 pp for a period of 2 months. This rough assessment reflects the experience of the first wave of lockdowns introduced in the spring of 2020, when it turned out that a vast majority of jobs that: are performed in the open air, where the risk of infection is reduced; closed spaces that can be arranged so as to decrease direct contact of workers, such as factories or office buildings; can be performed remotely, did not suffer from significant curtails or delays. The jobs which were highly affected with a lockdown policy were those which included direct contact with a customer or a direct contact of a group of people in a closed space, including: shops, restaurants, hotels and tourist infrastructure as well as cultural institutions. As a result only relatively small part of an economy got closed down completely with a lockdown. Our assessment of lockdown's severity seems to go in line with actual economic records, as it enables us to generate a fall of output that reaches the level of about 8% compared to the OECD average of 9.8% drop in the second quarter of 2020. Furthermore, in order to separate an impact of a single lockdown episode on an economic system, we assume that after the lockdown societies behave according to standard sanitary restrictions.

Our results show clearly that a lockdown episode results not only in the reduction of output, but also in a drastic fall of investments. At the same time we witness only moderate falls of capital level, which results from the fact that an economic downturn is highly limited in time. Finally an unemployment rate might temporarily go up, reaching relatively high levels. What is important, the depth of recession induced by the lockdown does not depend on the style in which a lockdown is introduced. No matter whether we follow Scenario 2 and introduce lockdown in an immediate way, or do it gradually, as in Scenario 3, macroeconomic variables fall by almost the same amount. What is truly important is the duration of economic downturn induced by the lockdown. It might be easily noticed that a lockdown which lasts for 2 months generates a fall of economic activity which vanishes after 24 weeks, i.e. within half of the year, when an economic recovery begins with a period of increased activity.

According to our results we face a clear trade-off between the duration and severity of recession induced by an epidemic. If we decide to shape our policy according to Scenarios 2 or 3 the changes of economic activity might be abrupt but short-lived. In case of Scenarios 1 or 4 the falls of economic activity might not be as deep, but rather permanent.

Results of the analyses related to Scenarios 2 and 3 enable us also to compare the efficiency of an immediate and gradual lockdown. It turns out that a widespread opinion that we should introduce lockdowns gradually so as not to disrupt economic system does not find confirmation in formal economic modeling. Gradual lockdowns, which are initially to weak to stop the spread of disease already curtail economic activity, reducing the level of output below its steady state level. At the same time as they do not change the dynamics of an epidemic they unnecessarily prolong the duration of an intervention and thus are suboptimal compared to an immediate lockdown.

One of the most important assumptions underlying results presented in this section concerns the strength of labour productivity reduction during the lockdown phase, which was chosen arbitrarily, in order to recreate an economic reaction that was observed in real economic data from the 2nd quarter of 2020. In order to test the robustness of our conclusions, we present the estimates of Scenario 2 for the case in which the lockdown cuts off productivity at the baseline level of 85% of its steady state value, together with the results obtained under the assumption that it falls to the level of -10 pp. and -20 pp. of the baseline value. Labour productivity paths simulated under these scenarios are presented in Figure 16. Conditional forecasts of the macroeconomic variables obtained for these productivity shocks are available in Figure 17.

Analysis of the outcomes enables us to infer that despite the fact that deeper changes of labour productivity result in more pronounced swings of macroeconomic variables, there is no evidence that such changes might affect the duration of the recession triggered by the lockdown. This conclusion is of major importance, as it confirms our finding concerning the trade-off between the severity and

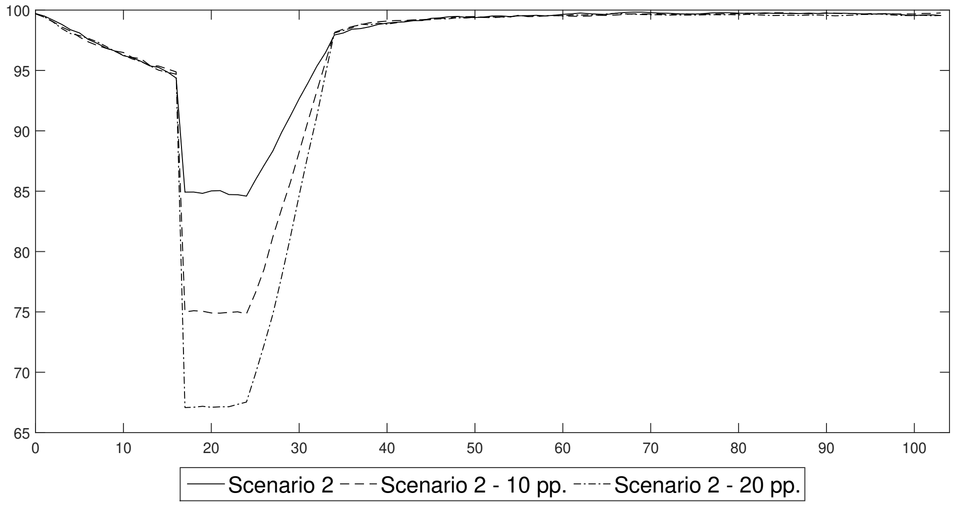

Figure 16. Labour productivity under Scenario 2 - robustness tests

duration of economic consequences of epidemic and thus validate it as a foundation of an efficient prevention and control policy.

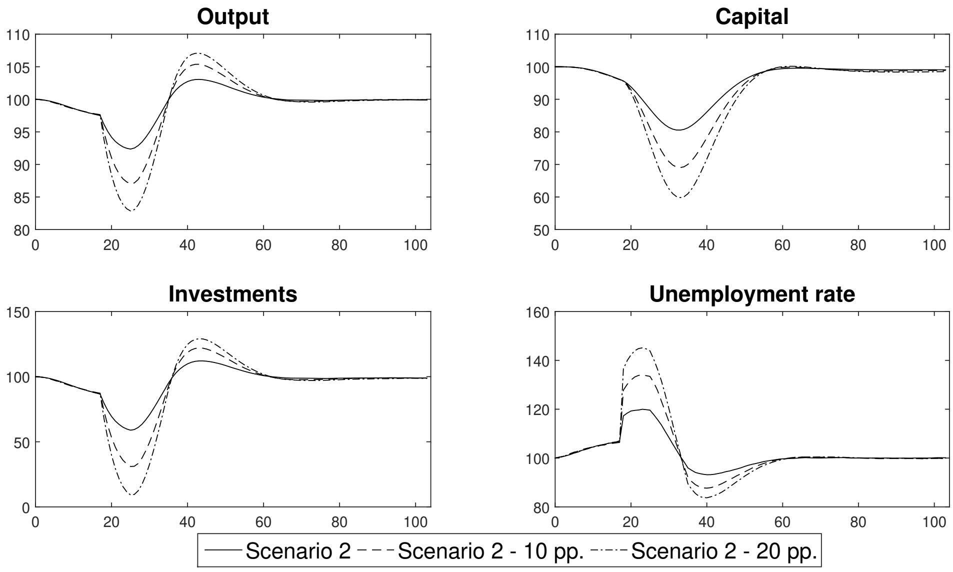

Figure 17. Conditional forecasts of major macroeconomic indicators under Scenario 2 - robustness tests

7. Policy implications

Results of the analyses performed in Section 6 enabled us to draw important conclusions with respect to the range and composition of desired prevention and control schemes aimed at the reduction of negative economic consequences of an epidemic. They support the use of lockdowns as an efficient tool in the fight with disease spread and reinstate the benefits of their immediate introduction. As such, our conclusions are mostly at odds with the widespread conviction that we should strive to keep at least part of an economy open at all costs.

Under these circumstances we should consider a policy based on the interchangeable use of lockdowns and periods of mild restrictions as a viable alternative to the currently dominant strategies of gradual intervention. In such a case lockdowns should be immediate and strict enough to stop the spread of the virus. It is important to minimise their duration in order to decrease negative economic consequences of reduced activity. In the periods of mild restrictions increases in the level of professional and private activity should be introduced gradually in order to decrease the pace of infections and lengthen the time between consecutive lockdowns.

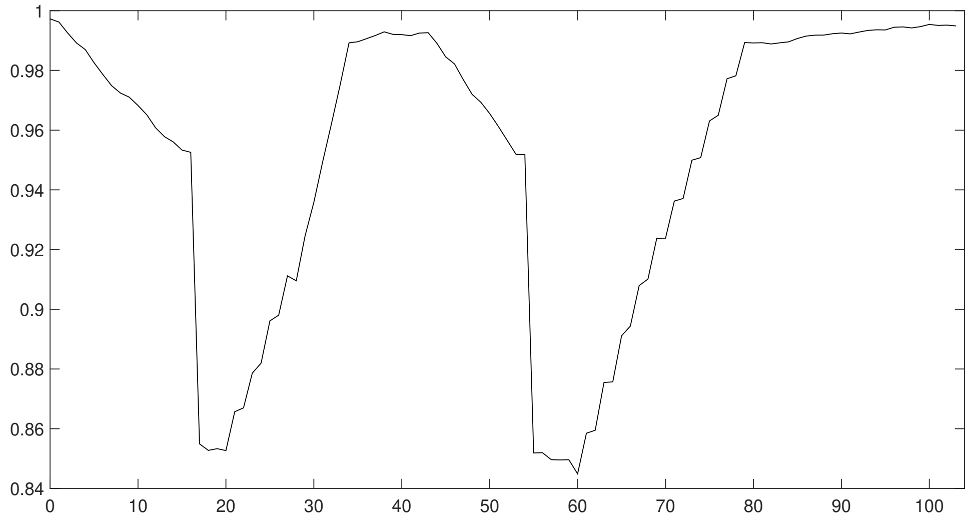

Figure 18. Labour productivity under recurrent lockdowns

Figure 18 illustrates the scenario of introducing recurrent lockdowns in the economy. In the case of the first lockdown, we make the same assumptions as in the second scenario presented in section 4.2. Both lockdowns were introduced as a mobility restrictions that modify the grid and interactions in the neighborhood. The grid is also dynamically optimized throughout the simulation run. We assume that the lockdown effect is perpetuated by a part of society, so their mobility is for some time lower despite the opening up of branches of the economy. During this period, the number of cases and mortality are low, and productivity is higher. After the transition period, when the mobility of agents increases, the number of infected also increases, which in turn forces the introduction of another lockdown. In this scenario the productivity of a healthy agent is not constant and may be lower than 1 during lockdowns and the open-up phases. As in case of the second scenario, the productivity differential also reflects the varying degrees of impact of epidemic on relevant sectors of the economy. We accept the possibility that this effect is not exactly the same in the event of a subsequent lockdown (it may affect the shape of the productivity curve in the open-up phase). The open-up phase of the second lockdown was carefully planned and the shape of the curve reflects strategy of closing and gradual opening of sectors of the economy.

The macroeconomic consequences of recurrent lockdowns are depicted in Figure 19. The outcomes prove that consecutive lockdowns produce temporary economic downturns of limited duration. Monthly periods of a strict decrease of economic activity combined with gradual open-up phase result in an approximately 4.5-month fall of economic activity below its steady state level. What is important, after the lockdown-phase a period of increased economic activity occurs. This result might play crucial role in the assessment of proposed strategy, as it enables an economy to make up for some of the losses right within an epidemic episode. Such a turn of events might play an important role in ensuring the accumulation of reserves, which will help the companies to survive further lockdowns. This feature of the recursive lockdowns' strategy distinguishes it from the scenarios that assume lack of targeted intervention, presented in Section 4, which would result in permanent reduction of economic activity lasting throughout the whole analysed period. As such, if rationally used and properly structured, a lockdown strategy might be more convenient for companies than initially though.

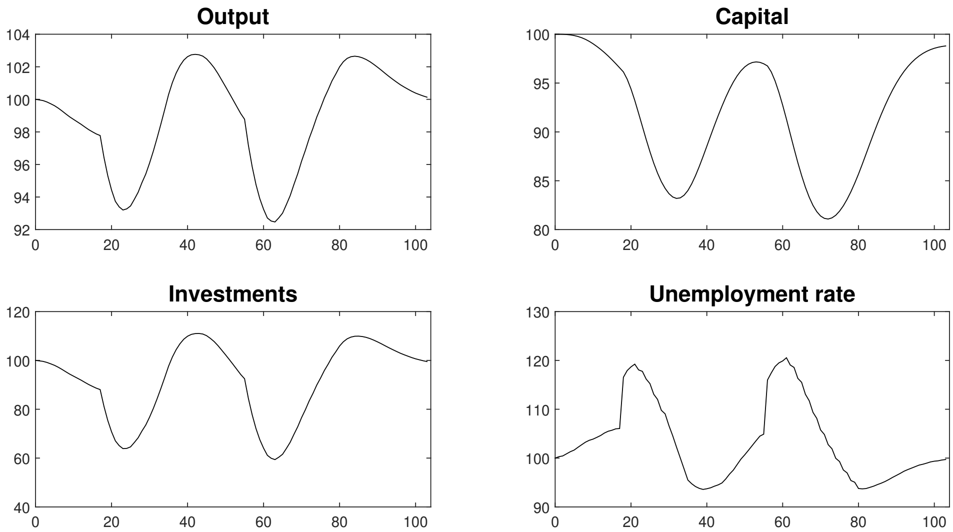

Figure 19. Conditional forecasts of major macroeconomic indicators under recurrent lockdowns

The chances of success under recursive lockdown strategy might be boosted significantly if the government introduces some additional provisions that were not yet included in the macroeconomic model presented above. Firstly, according to the rational expectations hypothesis when planning their economic activity people use all the available information. If so, open adoption and commitment to the proposed policy by the government might result in better preparedness of economic entities for the lockdown phase. Public presentation of draft lockdown schedules will allow entities to squeeze their actions within the mild restrictions phases in order to acquire reserves for the periods of reduced activity. Knowing that lockdown is a temporary and strictly controlled situation will make decisions about the future of economic entities burdened with less uncertainty, which will translate into lower volatility of macroeconomic categories and lower cost of an epidemic.

Secondly, the model does not yet account for the role of fiscal policy, which might be an important source of economic stimulation in the lockdown periods. Wisely framed programs of financial relief might result in reduction of a potential number of firms' bankruptcies, while employment support programs binding employment subsidies with restrictions in dismissal of employees might limit the volatility observed at the labour market. Such an approach might have decisive impact on the reduction of social costs of pandemic episode and play an important role in the process of maintenance of social mobilisation in the fight against the disease.

Thirdly, current version of the model ignores the costs of layoffs, including the labour contracts termination periods and severance payments. The same arguments applies to the costs of hiring new employees in the periods of increased activity. In the absence of the aforementioned features, the model might overvalue potential benefits of firing unproductive workers. As a result observed reactions of the employment and unemployment rates might overestimate the negative labour market effects of lockdown episodes.

Finally, it should be noted that the model still lacks some of the features that might potentially increase the scale of negative consequences of the lockdown policy. The most important of them being the lack of firms entry and exit. In such a case the depth of the recession induced by the lockdown might be slightly underestimated. An impact of that effect should however be balanced by the contradictory tendencies resulting from the factors named above, as well as from the fact that according to the provided scenarios we do only limit our analyses to relatively short lockdown experience, which should be bearable for the majority of companies.

8. Conclusions

This paper presents the results of examination of COVID-19 prevention and control schemes that was performed using the DSGE model with an agent-based epidemic component. Proposed methodology constitutes new approach to the problem, and demonstrates high potential for further use by providing reasonable assessment of differentiated epidemic scenarios. It provides clear benefits compared to the traditional approach of epidemic models such as SIR model and its straightforward transformations, as it provides for introduction of much more elaborate dynamics of the disease, including the consequences of spatial distribution of people and their social mobility. As a result the methodology used in our paper enables us to recreate a number of realistic prevention and control schemes and to assess their potential impact on the number of major macroeconomic indicators.

The research undertaken above was designed in an effort to broaden the existing scientific perspective concerning the use and efficiency of epidemic prevention and control schemes. It addressed two of the most interesting economic questions raised by the COVID-19 pandemics. The first of them concerned the reasonableness of the use of lockdowns as an epidemic countermeasure, while the second tackled the issue of the efficient scale and composition of such lockdown. The outcomes proved meaningful in both respects. Firstly, we have shown that an introduction of prevention and control schemes significantly reduces both the death toll and the overall level of economic disturbance, compared to the scenarios in which the persistent spread of COVID-19 is allowed. The falls of economic activity in the case of lockdowns are deeper but more compacted than in the case of unlimited spread of the virus, in which the pace of economic growth and capital accumulation is permanently lowered, while the societies have to cope with persistent and high unemployment. Secondly, adopted methodology enabled us to compare the efficiency of two major lockdown strategies that are currently in use: the one in which lockdown is immediate and deep enough to curtail the transmission of infections versus an approach in which lockdown is introduced gradually. It turns out that the probability that gradual changes are deep enough to stop the spread of coronavirus is relatively low, which results in extension of the period which precedes the actual lockdown, when an economy is already suppressed but no advances in terms of the pace of a virus spread are observed. According to our results this period is forlorn from an economic point of view and thus an economy would be better-off if the lockdown were introduced in a decisive yet efficient way. This observation is of major importance as it opposes a widespread belief that we should strive to keep an economy at least partially open as long as possible.

The outcomes of our research provide us with an interesting yet currently much overlooked conclusion concerning advisable shape of anti-COVID-19 policy. It turns out that lockdowns should not be perceived as a choice of last resort, but rather as a standard safety procedure introduced when the number of infections exceeds reasonable limits. Under certain provisions they should not be as damaging for an economy as it was earlier thought. Provided that people behave in a responsible way when going out of a lockdown and keep some standard safety provisions when they return to their professional activities, lockdowns enable us to limit significantly the duration of a period when negative economic consequences of a spike of infections are experienced. If so, we have reasons to presume that contingent on a proper informational strategy, a series of efficient lockdowns intertwined with periods of relatively normal activity might result in lower economic and social costs of pandemics than allowance to spread freely across the society. This is mostly due to the fact that in such a case we limit negative medium and long term consequences of an epidemic.

It should be noted that the results presented in this paper are still non-exhaustive and thus prone to some minor deficiencies, as this publication presents introductory outcomes of the analyses that we find interesting enough to turn into a more comprehensive research project investigating the macroeconomic consequences of COVID-19 pandemic. The model does not fully account for the complexity of the processes observed in a real economy and society. In order to make our analyses more approachable we have decided to leave aside such issues as: possible seasonality of infections, which might be an important factor that explains the dynamics of the pandemic observed in the northern hemisphere; the problem of herd immunity, which might be an important yet in our view not yet fully scientifically confirmed aspect of COVID-19 containment policies (there is still insufficient scientific evidence on the persistence of the IgG and IgM antibodies after a successful COVID-19 recovery); the problem of endogeneity of decisions concerning labour market participation in the pandemic period raised by Eichenbaum et al. [4]; the dynamics of the labour market response, which take place immediately after the shock, not accounting for the costs of hiring/firing of workers, employment contracts termination periods and severance payments; lack of firms entry and exit effects, which might affect the estimates concerning the depth of the economic downturn; fiscal interventions that might possibly diminish the negative toll of COVID-19 epidemic. Each of these issues constitute a separate research topic that might result in a standalone research paper. As a consequence our results should be approached with due restraint.

Author Contributions: Conceptualization, J.K-M. and P.W.; methodology, J.K-M. and P.W.; software, J.K-M. and P.W.; validation, J.K-M. and P.W.; formal analysis, J.K-M. and P.W.; investigation, J.K-M. and P.W.; resources, J.K-M. and P.W.; data curation, J.K-M. and P.W.; writing–original draft preparation, J.K-M. and P.W.; writing–review and editing, J.K-M. and P.W.; visualization, J.K-M. and P.W.; project administration, J.K-M. and P.W.; funding acquisition, J.K-M. and P.W.

Funding: The research of J.Kaszowska-Mojsa was supported by the Institute of Economics, Polish Academy of Sciences. The research of P. Włodarczyk was supported by the University of Łódź, Faculty of Economics and Sociology.

Conflicts of Interest: The authors declare no conflict of interest. The views contained in this study express only the opinions of the authors and may not be attributed to any of the institutions with which they are affiliated or with which they cooperate on a professional basis. The paper has been submitted for review on 31 October 2020 to economic journal and it was sent to Lodz Economics Working Papers on 9 November 2020 to disseminate the research results.

Abbreviations

The following abbreviations are used in this manuscript:

ABM	Agent-Based Modelling
AR(1)	Autoregressive model of order 1
COVID-19	Coronavirus Disease 2019
COVID-ABS	Coronavirus Disease 2019 Agent-Based Simulation
CSO	Central Statistical Office
DSGE	Dynamic Stochastic General Equilibrium
FOC	First Order Condition
GUS	Central Statistical Office
pp.	percentage points
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
SIR	Susceptible-Infectious-Recovered model
SEIR	Susceptible-Exposed-Infected-Recovered model

References

1. Hunter, E.; Mac Nameeb, B.; Kellehera, J. A Taxonomy for Agent-Based Models in Human Infectious Disease Epidemiology, *J. Artif. Soc.* **2017**, *20*, 3. doi: 10.18564/jasss.3414
2. Ajelli, M.; Gonçalves, B.; Balcan, D.; Colizza, V.; Hu, H.; Ramasco, J.; Merler, S.; Vespignani, A. Comparing large-scale computational approaches to epidemic modeling: Agent-based versus structured metapopulation models. *BMC Infect Dis* **2010**, *10*, 190. doi: 10.1186/1471-2334-10-190
3. Dunham, J. An agent-based spatially explicit epidemiological model in MASON. Journal of Artificial Societies and Social Simulation **2005**, *9*, 1.

4. Eichenbaum, M.; Rebelo, S.; Trabandt, M. The Macroeconomics of Epidemics. *NBER WP* **2020**, 26882, 1–35. doi: 10.3386/w26882
5. Mihailov, A. Quantifying the Macroeconomic Effects of the COVID 19 Lockdown: Comparative Simulations of the Estimated Galí Smets Wouters Model. *Univ. of Reading Disc. Paper* **2020**, 2020-07, 1–32.
6. Yanga, Y.; Zhangb,H.; Chenc, X. Coronavirus pandemic and tourism: Dynamic stochastic general equilibrium modeling of infectious disease outbreak. *Ann Tour Res.* **2020**, *83*, 2–6. doi: 10.1016/j.annals.2020.102913
7. Bayraktar, E.; Cohen, A.; Nellis, A. A Macroeconomic SIR Model for COVID-19. *medRxiv Preprints* **2020**, 1–23. doi: 10.1101/2020.06.22.20137711
8. Toda, A. Susceptible-Infected-Recovered(SIR) Dynamics of Covid-19 and Economic Impact, *Covid Economics, Vetted and Real-Time Papers* (CEPR) **2020**, 1, 1–15.
9. Jordà, O.; Singh, S.R.; Taylor, A.M. Longer-run Economic Consequences of Pandemics, *NBER WP* **2020**, 26934, 3–20. doi: 10.3386/w26934
10. Guerrieri, V.; Lorenzoni, G.; Straub, L.; Werning, I.; Macroeconomic Implications of COVID-19: Can Negative Supply Shocks Cause Demand Shortages?, *NBER WP* **2020**, 26918. doi: 10.3386/w26918
11. Cuevas, E. An agent-based model to evaluate the COVID-19 transmission risks in facilities, *Comput Biol Med.* **2020**, 121, 1–12. doi: 10.1016/j.compbiomed.2020.103827
12. Silva, P.; Batista, P.; Lima, H.; Alves, M.; Guimarães, F.; Silva, R. COVID-ABS: An agent-based model of COVID-19 epidemic to simulate health and economic effects of social distancing interventions, *Chaos Soliton Fract* **2020**, *139*, 1–12. doi: 10.1016/j.chaos.2020.110088
13. Shamil, M.S.; Farheen, F.; Ibtehaz, N., Khan, I.; Rahman, M. An Agent Based Modeling of COVID-19: Validation, Analysis and Recommendations. *medRxiv Preprints* **2020**, 1–17, doi: 10.1101/2020.07.05.20146977
14. Hoertel, N.; Blachier, M.; Blanco, C.; Olfson, M.; Massetti, M.; Sánchez Rico, M., Limosin, F., Leleu, H. A stochastic agent-based model of the SARS-CoV-2 epidemic in France. *Nat Med* **2020** *26*, 1417–1421. doi: 10.1038/s41591-020-1001-6
15. Wallentin, G., Kaziyeva, D., Reibersdorfer-Adelsberger, E. COVID-19 Intervention Scenarios for a Long-term Disease Management. *Int. J. Health Policy Manag.* **2020**, In press, 1–9. doi: 10.34172/ijhpm.2020.130
16. Currie, Ch.; Fowler, J.; Kotiadis, K.; Monks, T.; Onggo, B.; Robertson, D.; Tako, A. How simulation modelling can help reduce the impact of COVID-19, *J. Simul* **2020**, *14*, 83–97. doi 10.1080/17477778.2020.1751570
17. Bertozzi, A.; Franco, E.; Mohler, G.; Short, M.; Sledge, D. The challenges of modeling and forecasting the spread of COVID-19. *Proc Natl Acad Sci U S A* **2020**, *117*, 16732–16738. doi: 10.1073/pnas.200652011
18. Klôh, V.; Silva, G.; Ferro, M.; Araújo, E.; Barros de Melo, C.; Pinho de Andrade Lima, J.R; Rademaker Martins, E.The virus and socioeconomic inequality: An agent-based model to simulate and assess the impact of interventions to reduce the spread of COVID-19 in Rio de Janeiro. *Braz J of Hea Rev* **2020**, *3*, 647–3673. doi: 10.34119/bjhrv3n2-192
19. Maziarz, M.; Zach, M.. Agent-based modelling for SARS-CoV-2 epidemic prediction and intervention assessment: A methodological appraisal. *J. Eval. Clin.* **2020**, *26*, 1352–1360. doi: 10.1111/jep.13459
20. Kano, T.; Yasui, K.; Mikami, T.; Asally, M.; Ishiguro, A. An agent-based model for interrelation between COVID-19 outbreak and economic activities. Available online: https://arxiv.org/abs/2007.11988 (accessed on 29 October 2020)
21. Brotherhood, L., Kircher, P., Santos, C., Tertilt, M. An Economic Model of the COVID-19 Epidemic: The Importance of Testing and Age-Specific Policies, *IZA Discussion Paper* **2020**, 13265, 1–68.
22. Brottier, I. COVID 19: The Good, the Bad and the Agent Based Model. Available online: https://www.anylogic.com/blog/covid-19-the-good-the-bad-and-the-agent-based-model/ (accessed on 29 October 2020).
23. Adam, D. Special report: The simulations driving the world's response to COVID-19. How epidemiologists rushed to model the coronavirus pandemic. Available online: https://www.nature.com/articles/d41586-020-01003-6 (accessed on 29 October 2020).
24. Wolfram, Ch. Agent-Based Network Models for COVID-19. Available online: https://www.wolframcloud.com/obj/covid-19/Published/Agent-Based-Networks-Models-for-COVID-19.nb (accessed on 20 October 2020).
25. Galí, J. *Monetary policy, inflation, and the business cycle. An introduction to the New Keynesian framework*, 1st ed.; Princeton University Press: Princeton, US, 2008; pp. 3–224.

26. Christiano, L.; Eichenbaum, M.; Evans, C. Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy. *J Polit Econ* **2005**, *113*, 1–45.
27. Galí, J. *Unemployment Fluctuations and Stabilization Policies. A New Keynesian Perspective*, 1st ed.; MIT Press: Cambridge, US, 2011; pp. 2–120.
28. Galí, J. *Monetary Policy, Inflation, and the Business Cycle. An Introduction to the New Keynesian Framework and Its Applications*, 1st ed.; Princeton University Press: Princeton, US, 2015; pp. 2–224.
29. Galí, J.; Smets, F.; Wouters, R. Unemployment in an Estimated New Keynesian Model. In *NBER Macroeconomics Annual 2011*, 1st ed.; Acemoglu, D.; Woodford, M., Eds.; Chicago University Press: Chicago, US, 2012; 26, pp. 329–360.
30. King, R.G.; Plosser, C.I.; Rebelo, S.T. Production, growth and business cycles: I. The basic neoclassical model *J. Monet. Econ.* **1988**, *21*, 195–232. doi: 10.1016/0304-3932(88)90030-X
31. Smets, F.; Wouters, R. Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach. *Am Econ Rev* **2007**, *97*, 586–606. doi: 10.1257/aer.97.3.586
32. Abel, A. Asset Prices under Habit Formation and Catching up with the Jonses *Am Econ Rev* **1990**, *80*, 38–42.
33. Christiano, L.; Trabandt, M.; Walentin, K. Involuntary Unemployment and the Business Cycle. *Rev. Econ. Dyn* **2020**, In press. doi: 10.1016/j.red.2020.05.003
34. Calvo, G. Staggered prices in a utility-maximising framework *J. Monet. Econ.* **1983**, *12*, 383–398. doi: 10.1016/0304-3932(83)90060-0
35. Merz, M. Search in the labor market and the real business cycle *J. Monet. Econ.* **1995**, *36*, 269–300. doi: 10.1016/0304-3932(95)01216-8
36. Armington, P. A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers* **1969**, *16*, pp. 159–178. doi: 10.2307/3866403
37. Green, H. *Aggregation in Economic Analysis*, 1st ed.; Princeton University Press: Princeton, US, 1964; pp. 2–140.
38. Dixit, A. & Stiglitz, J. Monopolistic Competition and Optimum Product Diversity. *Am Econ Rev* **1977**, *67*, 297–308. doi: 10.7916/D8S75S91
39. Christiano, L.; Trabandt, M.; Walentin, K. DSGE Models for Monetary Policy Analysis. In *Handbooks in Economics. Monetary Economics*, 1st ed.; Friedman, B., Woodford, M., Eds.; North-Holland: Amsterdam, Netherlands, 2011; Volume 3A, pp. 285–367.