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RESEARCH ARTICLE

Limited containment options of COVID-19 outbreak revealed by regional agent-based simulations for South Africa [version 1; peer review: 1 approved with reservations, 1 not approved]

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Abstract

Background: COVID-19 has spread from China across Europe and the United States and has become a global pandemic. In countries of the Global South, due to often weaker socioeconomic options and health care systems, effective local countermeasures remain debated.
Methods: We combine large-scale socioeconomic and traffic survey data with detailed agent-based simulations of local transportation to analyze COVID-19 spreading in a regional model for the Nelson Mandela Bay Municipality in South Africa under a range of countermeasure scenarios.
Results: The simulations indicate that any realistic containment strategy, including those similar to the one ongoing in South Africa, may yield a manifold overload of available intensive care units. Only immediate and the most severe countermeasures, up to a complete lock-down that essentially inhibits all joint human activities, can contain the epidemic effectively.
Conclusions: As South Africa exhibits rather favorable conditions compared to many other countries of the Global South, our findings constitute rough conservative estimates and may support identifying strategies towards containing COVID-19 as well as any major future pandemics in these countries.

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Introduction

The first cases of the coronavirus disease COVID-19 were confirmed on December 29, 2019 in China[1]. Due to high contagiousness[2], the disease has spread rapidly[3,4] and by April 2020 the World Health Organization (WHO) had confirmed[5] about 1.6 million cases worldwide. Consequently, the COVID-19 epidemic was declared a pandemic as it started to impact economies worldwide. However, epidemiological expertise lagged behind the exponential spread in this specific situation. In an attempt to contribute to the scientific assessment of the COVID-19 pandemic, we quickly derived first results and were able to make first predictions for the South African COVID-19 development. The significance of timely countermeasures could be seen in the development of infections in the United States, where cases surged from 1,678 to 307,318 between March 16, and April 6, 2020[6,7]. Therefore, our research applied agent-based simulations to assess the effectiveness of countermeasures at an early stage of the COVID-19 pandemic and the following paper displays the state of literature and infection figures for the period of March and April 2020.

Most countries of the Global South were affected as well, often with reported case numbers just beginning to surge[8]. However, the reported low numbers in April, e.g. about 9000 cases in all of Africa, may be biased as only few individuals have been tested, see[9] for the example of South Africa, and also[10]. Furthermore, such countries operate under vastly different socio-economic conditions, with larger social inequality, distinct transportation options and weaker health care systems compared to those of most countries in the global north[11,12,13], such that core characteristics of potential COVID-19 spreading dynamics and thus the effectiveness of specific countermeasures remain largely unknown for countries of the Global South.

The transmission of COVID-19 is currently thought to occur through direct inter-person droplet-based infections through coughing and sneezing, with possible additional infection paths through aerosols and via contaminated surfaces. Symptoms often occur only after an incubation period of several days, with many infected responding entirely asymptomatic. Contagion may also occur via such symptom-free carriers, posing a challenge for tracing and estimating spreading patterns[14]. Transmission predominantly occurs through interactions while being at home, being at work, using shared transportation modes or during group-based leisure activities. In many countries of the Global South, most of these social activities occur under conditions drastically different from those in, for example, Europe or the U.S.. For instance, these countries feature, on average, more people per household, higher unemployment rates, more manual and lower payed work[15,16] and much of publicly available transportation services used by the middle and low-income population are offered as paratransit shared-mobility services[17,18]. Moreover, public health care services are different and often less well equipped than in countries of the Global North[13,19].

As a paradigmatic region offering large-scale data availability, we consider the Nelson Mandela Bay Municipality (NMBM) in South Africa to study scenarios of COVID-19 spreading dynamics and the impact of countermeasures. We combine socio-economic and travel survey data from more than 100,000 people[20], about 10% of the local population, based on employment status, household size, age group and income level together with a detailed 24-hour travel diary component integrated into an agent-based traffic simulation (see Methods). The resulting contact network forms the basis for extended Susceptible-Infected-Recovered (SIR) model dynamics with parameters adapted to COVID-19[21]. Such agent-based simulations capture the inhomogeneity among the agents and are capable of modeling intricate nonlinear dynamic relationships between them, including a spreading rate that depends on the individual agent's detailed activities, their modes of transportation used, and their distance to each other[22].

To evaluate the impact of various policy measures on the course of the disease, we systematically compare several scenarios by varying simulation parameters accordingly (see Methods). First, a *baseline* scenario without any counter-measures; second, a *default* scenario in line with the current measures implemented in South Africa as of early April 2020[23]. These include the shutdown of childcare and educational institutions, the prohibition of leisure activities of any kind and cutting shopping activity options by about 70%. Moreover, work related and "other" activities (for example trips to health care facilities and visits to public institutions) and travelling as passenger in a car are reduced by 80% and formal and informal public transport is reduced by 30%. Third, as a harsher variation of the lockdown that may be achievable in principle, we study the effect of a *realistic lockdown* scenario, increasing the restriction of activities related to work, shopping, leisure, and "other" by 90% while childcare, educational activities as well as formal and informal public transport are completely shut down. Finally, we consider a theoretical *complete lockdown* where all travel and outside activities are prohibited. All countermeasures come into effect 7 days after an initial infection of 100 people. We furthermore investigate additional simulations that start with the (currently enacted) default measures and introduce the realistic lockdown scenario after a number of days. Our results may inform and complement the ongoing discussion around tightening, loosening, introducing or repealing certain countermeasures.

Methods

Transport simulation

For the transport simulation, we employ MATSim version 12.0-2019w48-SNAPSHOT[24]. The analysis relies on the population data file provided by Joubert[20]. It processes travel diaries from the 2004 Travel Survey to compute a synthetic population sample of the Nelson Mandela Bay Municipality (NMBM). Table 1 outlines the descriptive statistics of the synthetic agents and the modal split. It becomes apparent that the minibus taxis are the backbone of the region's transport system. Private transport such as passenger cars play a rather marginal role. This difference underlines the interdependence of geographical, historical and economic characteristics of the region.

We employ the Demand Responsive Transport (DRT) framework for MATSim[26] to include the informal minibus taxi transit. In the underpinning MATSim, agents walk to a bus stop and request a DRT vehicle (in this case a minibus taxi). Their ride is pooled with rides of other agents with similar destinations. The simulated routing is more flexible than in reality, since the minibus taxis operate on a stop-based system with routes. Due to a lack of data, this mode is implemented based on a door-to-door based operating scheme and pick ups waiting passengers from the stops. Consequently on the one hand the vehicles are less frequented but on the other hand travel longer distances with passengers on board to pick up customers in the city. This reduces the likelihood of being on a minibus with an infected person, but increases the contact time if an infected person is actually on board. The formal bus transport services in NMBM are provided by Algoa Bus Company[27]. Currently, all formal bus operations are suspended in NMBM. It can therefore be assumed that customers are substituting regular bus services with minibus taxis. The MATSim population file is modified accordingly.

Transport parameters

Due to the 10% population sample, the total capacity of the minibus taxis vehicles must be adapted to reflect the proportions in reality. In 2014, a total of 2,374 minibus taxis operated in NMBM with an average capacity of 15 persons[25]. As scaling the capacity of minibus taxis to 1.5 passengers would strongly underestimate the infections during minibus taxi trips, several test scenarios with different fleet sizes and passenger capacities were carried out.

Due to the operating scheme of door-to-door DRT a reduction either in fleet size and/or passenger capacity of the vehicles would lead to a high rejection rate and accordingly high infection numbers at home facilities that could bias the simulation results. For this reason, the number of vehicles is chosen with respect to the trade-off between capacity utilisation and the rejection rate. A fleet of 2,374 vehicles with a capacity of 15 optimises these criteria and is introduced into the model. The vehicles are placed randomly in the area at the beginning of the simulation, although in reality they wait for customers at designated places at the beginning of the day and start their tour when a certain degree of occupancy is reached.

Public minibus taxis are assumed to take an important role in the epidemic simulation, as both the probability and the intensity of contact are assumed to be high. Moreover, people with different places of work and residence mix up at this small space.

Epidemic simulation

The model relies on the MATSim-based Episim-framework to simulate the epidemic spreading in the research area. The following briefly summarises both the functionality of the default Episim configuration and the parametric adaptions to the NMBN. It is important to note that the package is still in a early stage of development. For the following simulations, we used the latest version dated April 11, 2020 from the master branch (see https://github.com/matsim-org/matsim-episim/tree/85ca164a472b7f60117a51a365daed1eaf376199).

Episim is based on a traditional SIR model, which is a common model for the analysis of epidemics[28] and has been continuously improved, e.g. by[29,30,31]. The basic mechanism is that people go through different stages during an epidemic, and have different characteristics with each transition. In short, initially all persons are susceptible for a disease and, over time, become infected with a given probability, partly influenced by individual characteristics. Later on, they recover. The states and transitions are usually extended to a more complex framework and include quarantine, seriously sick and critical patients in order to account for policy measures and the need for either hospital beds or ICUs.

The infection process is based on a probabilistic model and occurs in "containers". These containers represent locations where several agents may interact, such as households, workplaces or transport vehicles, and are computed based on the information from NMBM MATSim simulation output event data. These chronicle all trajectories covered by agents during the day and the vehicles and facilities they visited and stayed at. Once a susceptible and a contagious agent stay in the same container, an infection occurs with a certain probability, which is described by equation 1 (see below).

Table 1. Descriptive statistics of the Nelson Mandela Bay Municipality population sample. The 114,346 agents represent a 10% sample of the total population of NMBM. The trip distribution by transport mode shows the high prevalence of low cost transport modes (walk and minibus taxi) compared to private car usage. (Data from[20,25]).

Variables	Values
Number of Agents (10% Sample)	114,346
Mean age of agents (years)	30.27
Share of female agents	52.31%
Number of households	32,597
household size (persons per HH)	1 - 10
Average household size (persons per HH)	3.51
Mean annual household income (ZAR)	141,499
Number of minibus taxis (DRT)	2,347
Number of Legs with mode:	
Walk	208,694
Minibus taxi	104,730
Car (driver)	20,257
Car (non-driving passenger)	21,803
Train	265
Bike	158

Epidemic parameters

At the beginning of the simulation, 10 randomly selected agents (corresponding to 100 people) are initially infected. After 7 days of uncontrolled spread, various countermeasures are implemented. We consider the dynamics until the countermeasures are in effect for 60 days.

In Episim, infected agents undergo several state transitions before their infection is terminated. Since not all humans suffer equally from COVID-19, the agents follow different paths from infection to recovery. In the beginning of the simulation, all agents except the "Patients Zero" are initially healthy and thus *susceptible.* After an infection, an agent's state changes to *infected but not contagious,* due to incubation time. With the beginning of the fourth day after an infection, the agent's state changes to *contagious.* From this step on, the agent's differ in their behaviour. In the default scenario, 20% of the agents put themselves into quarantine. The idea of the simulation model is that only a certain share of those suffering from COVID-19 notices symptoms. In addition, it is to be expected that some infected persons will go into public despite symptoms. The self-quarantine lasts 14 days and is assumed to mitigate social contacts completely, even within the household. 4.5% of all infected agents become *seriously sick* on day 10 and of these, 25% become *critical* the following day. In this way, a distinction is made between patients who require regular medical care and those who are dependent on ICUs. Contagious agents recover 16 days after infection, whereas the infection of patients with severe conditions terminates after 23 days.

In reality, an infection would end by recovery or death. For usability reasons, every infected agent recovers in Episim. As recovered agents are assumed to be immune and no longer contagious, omitting death does not bias the further course. The same mechanism is applied for self-quarantined, who remain mobile in the simulation but are neither contagious nor susceptible.

The probability of agent n becoming infected at time t when leaving a container is given by

$$P_{n,t} = 1 - \exp\left[-\theta \sum_m q_{m,t} i_{nm,t} \tau_{nm,t}\right], \tag{1}$$

where q denotes the shedding rate (infectivity-parameter for the virus), i the contact intensity and τ the interaction duration of two persons, summed over all persons in contact with agent n. i is assumed to scale as d^{-3}, thus declining very fast with increasing distance. θ is introduced as a calibration parameter to shape the infection curve in a realistic way. Based on current infection data a tenfold increase of infected persons in 7 days is quite realistic for most countries without any interventions. In our framework, we thus set $\theta_{NMBM} = 0.000003$ in order to meet this condition.

Most of the contact intensities were left at their default since it is reasonable to assume that the contact intensities of most activities do not differ significantly from the values determined by[21]. The activities *work*, *shopping*, *dropby* and *other* were introduced so that the first two have the same contact intensity as *leisure* (5) and the other two take the values 7 and 3. It is assumed that due to the available space and seating arrangements in the minibus taxis, the contact between passengers in the minibus taxis is much higher than in formal public transport in Berlin. Since no reliable data on the contact intensity of passengers are available, we take the interaction intensity to be 20, compared to 10 in the default setting. Likewise, the contact intensity of being at home is doubled from 3 to 6 due to limited space, larger households and general living conditions.

Policy parameters

The countermeasures in the default setting, realistic lockdown and complete lockdown are described by modifiers to the activity rates of the agents, describing the reduction in the frequency of the respective activity. Table 2 lists all parameters for the scenarios studied.

Results and discussion

Direct model simulations in the four scenarios (Figure 1) reveal that a large fraction of the population becomes infected, not only for the baseline scenario without countermeasures (as expected), but also with the default countermeasures active as of this writing (April 11 2020), see Figure panels 1A and 1B. Even if scenarios of harsh but realistically possible or complete lockdown were enacted only seven days after reaching 100 infected people, the outbreaks would still become macroscopic, with tens of thousands of infected people (Figure 1C and 1D) in the NMBM alone. Across all scenarios enacted, outbreak dynamics also causes overload of the approximately ICU beds estimated as baseline for NMBM (Figure 1E,F). As a precondition for successful containment, lockdown needs to be implemented sufficiently early on (in particular less than 7 days after the first 100 infected, *not* the first 100 confirmed infected).

In all four scenarios, the outbreak strongly overloads the available intensive care unit (ICU) beds, with ten- to 100-fold overload in default and baseline scenario, respectively (see Figure 2A). Out of the total 267 ICU beds available in (public and private) hospitals in the whole Eastern Cape Province (data from 2008,[32]), only about 50 would be available for critical cases from the NMBM (scaled proportional to the relative population counts in 2011[33,34]). We additionally quantify the sustained pressure on the health care system by computing the cumulative overload λ of the health system as the total number of person days critical patients go without intensive care (Figure 2B),

$$\lambda = \int \Theta(c(t) - c_{\max})[c(t) - c_{\max}] \, \mathrm{d}t$$

where $\Theta(\cdot)$ denotes the Heaviside step function, $\Theta(x) = 1$ for $x \geq 0$ and $\Theta(x) = 0$ otherwise, $c(t)$ the number of critical cases at time t and $c_{\max}$ the available ICU capacity. The integral is taken over the entire time of simulation, 64 days after the 100 people are infected in NMBM. This cumulative measure λ thus quantifies the total long term overload of intensive care health services (and may be large even if the peak overload is small).

Table 2. Allowed share per activity in four scenarios. Episim allows to prohibit or restrict the practice of certain activities in order to simulate social distancing. Four sets of restrictions were implemented in the simulations. While in the baseline scenarios no measures are in power, a complete lockdown does not allow the population to leave their homes. Between those extreme cases, two different partial lockdowns are set up.

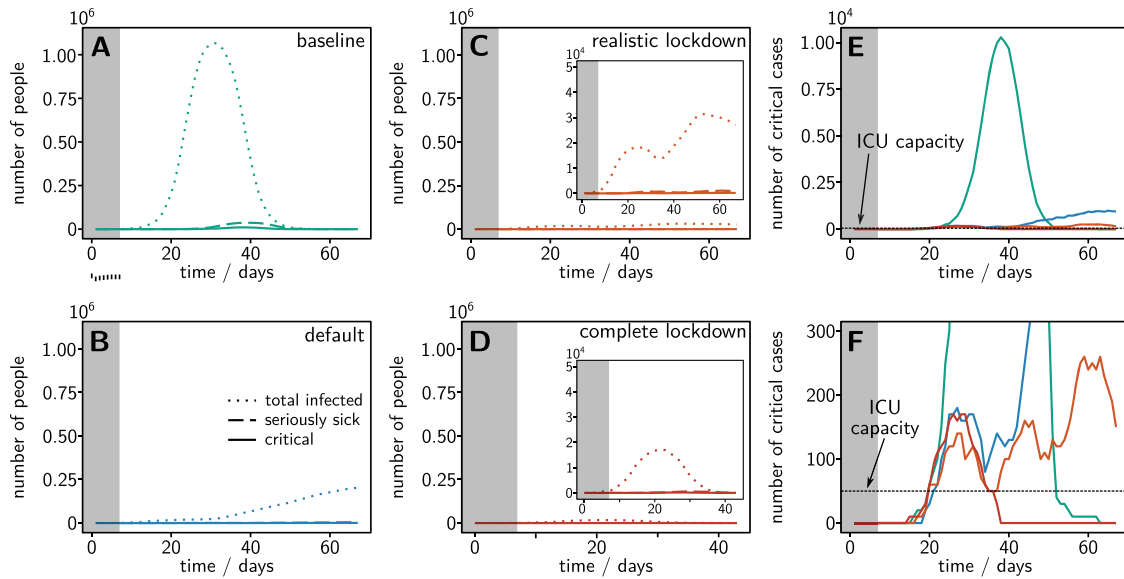| Scenario	Baseline	Default	Realistic	Lockdown
Home	1	1	1	1
Work	1	0.2	0.1	0
Minibus taxis	1	0.7	0	0
Leisure	1	0	0.1	0
KiGa and Prim. Educ.	1	0	0	0
Higher Education	1	0	0	0
Shopping	1	0.3	0.1	0
Dropby	1	0	0	0
Other	1	0.2	0.1	0

Figure 1. Distinct outbreak scenarios of COVID-19. Dynamics for the Nelson Mandela Bay Municipality, Eastern Cape, South Africa, with a total population of 1.15 million people. (A-D) Evolution of the number of infected (dotted lines), seriously sick (dashed) and critical (solid) patients in four different scenarios: (A) baseline without any countermeasures, (B) with default countermeasures in line with current conditions in South Africa, (C) with harsh realistic countermeasures shutting down 90% of all activities, and (D) with complete lockdown prohibiting any movement and group activities (infections within a household are still possible, see Supplementary Material for details). All countermeasures are initiated 7 days (grey shading) after the an initial infection of 100 people. (E) and (F) Number of critical cases requiring intensive care compared to the available ICU capacity (horizontal dashed line) for all four countermeasure scenarios. None of the scenarios reduces the number of critical cases sufficiently to guarantee intensive care (ICU) treatment for all critical patients.
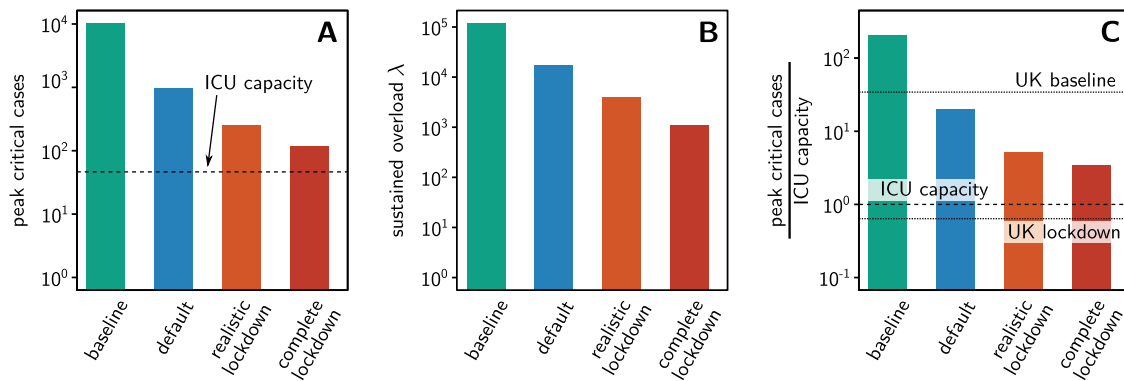

Figure 2. Overload of the health care system. (A) Maximum number of concurrent critical patients during the peak of the outbreak. The available ICU capacity (dashed line) is widely exceeded in all scenarios. (B) The measure λ for the sustained overload, counting the total number of person days that critical patients are without intensive care. (C) Relative exceedance of the ICU capacity at the peak of the outbreak. The potential consequences of COVID-19 in countries of the Global South becomes clear from the comparison to UK estimates[35] with about 35-fold overload without interventions (UK baseline, upper dotted line) and no overload with UK lockdown (lower dotted line) enforcing school and university closure, case isolation and general social distancing. Note the logarithmic vertical axes in all panels to make vast case number differences visible simultaneously with the capacity.

The potential severity of the outbreak in NMBM even with strong countermeasures, is especially evident when compared to that of the United Kingdom (UK) (Figure 2C). In the UK, ICU capacity would be exceeded by a factor of about 35 without any countermeasures, by a factor of about 2 with social distancing (similar to default in our simulations) and not at all with measures currently enacted[35]. In our NMBM scenario simulations, ICU capacity would be exceeded by a factor of more than 200 without any countermeasures, by factor of about 20 with default measures, by a factor of 5 with realistic lockdown and still by a factor of 3 even with complete lockdown. These numbers underline the strong fragility of
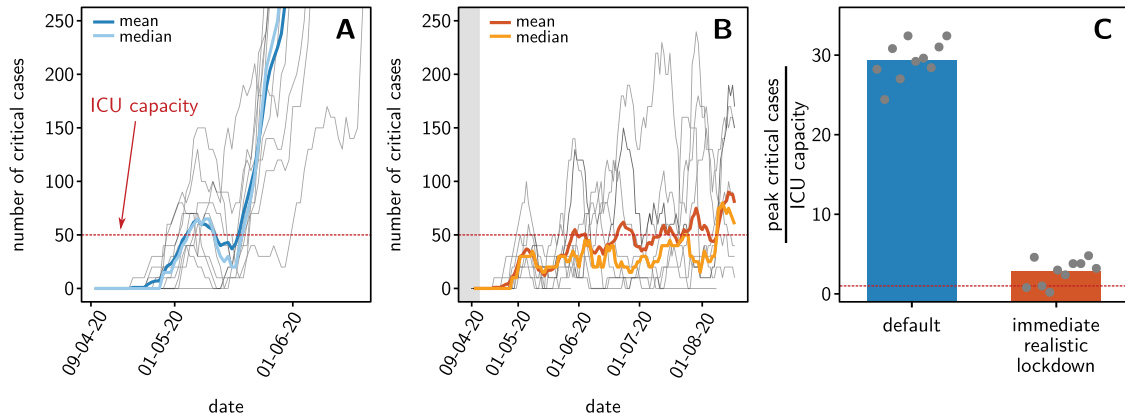
Figure 3. Confining the impact by rapid lockdown. Ten stochastic realizations of agent-based simulations (gray lines in (A) and (B)) show increasing typical number of critical cases, quantified by the ensemble mean (dark) and median (light). (A) Stochastic dynamics of the number of critical cases when keeping the currently active default measures in NMBM. The ICU capacity is exceeded in almost all realizations within two months. (B) Switching from *default* (currently roughly enacted in South Africa) to the *realistic lockdown* scenario, limiting all activity by 90%, four days after crossing 100 infected people (estimated from 30 actually reported cases) in NMBM (that is on April 13, 2020), yields an exceeded ICU capacity in 80% of realizations, at most five times above the available capacity. (C) Relative exceedance of available ICU capacity in both scenarios. Keeping a default would cause roughly 3000% overload whereas enacting a stricter lockdown on April 13th substantially reduces expected overload to less than 300% and may completely avoid an overload in best cases.

Table 3. Total number of infection events per location in the simulation scenarios. Each event represents an initial infection of one out of 114.346 total agents. While most infections occur at home due to prolonged and close contact, paratransit in terms of minibus taxis is the second largest driver of the spreading process, accounting for approximately 15% of all infection events in the baseline scenario. These numbers decrease under countermeasures and almost disappear under complete lockdown, where only a few people are initially infected before all travel is stopped. A comparison to artificial settings where infections during minibus transit are neglected demonstrate the importance of the minibus taxi service as a driver for the spreading, in particular under partial lockdown.

Scenario	Baseline	Default	Realistic	Lockdown
Scenarios with Minibus infection				
Home	75,259	39,629	9,063	1,774
Work	2,188	919	171	5
Minibus taxis	16,002	3,705	799	18
Leisure	3,105	524	206	0
KiGa and Prim. Educ.	13,560	2,745	690	1
Higher Education	579	119	41	0
Shopping	915	549	26	0
Dropby	22	3	1	0
Other	2,210	621	99	4
Scenarios without Minibus infection				
Home	83,747	17,421	3,417	1,091
Work	2,589	670	45	5
Minibus taxis	0	0	0	0
Leisure	4,075	392	91	0
KiGa and Prim. Educ.	16,581	2,068	142	2
Higher Education	822	74	8	0
Shopping	1,257	288	7	0
Dropby	28	1	0	0
Other	3,021	398	32	4

Table 4. Exact values of health care system overload measures for all simulation scenarios. During the first 6 days, the virus spreads uncontrolled. On day seven, countermeasures are initiated that restricts certain activities (see 2). The upper values result from simulations in which minibus taxis are possible locations of infection (presented in the main manuscript). The lower values are drawn from simulations, in which people could not become infected in minibus taxis (compare Table S3).

Scenario	Baseline	Default	Realistic	Lockdown
Scenarios with Minibus Infection				
Peak Newly Infected per Day	128,870	15,510	2,370	2,350
Peak Seriously Sick	36,890	5,170	1,090	570
Peak Critical	10,280	990	260	170
Peak Critical Cases per ICU	205.6	19,8	5.2	3.4
λ	118,320	16,965	4,055	1,100
Days until first ICU Overload	18	21	20	20
Scenarios without Minibus Infection				
Peak Newly Infected per Day	109,400	8,500	1,930	1,920
Peak Seriously Sick	34,720	2820	400	370
Peak Critical	9,030	750	130	120
Peak Critical Cases per ICU	180.6	15	2.6	2.4
λ	113,515	6,020	1,055	475
Days until first ICU Overload	20	26	24	23

the health care services by example of the NMBM. We expect similar orders of magnitude of capacity exceedance throughout South Africa and in many countries of the Global South.

Therefore, all realistic scenarios, including the default scenario currently enacted in South Africa, hardly seem capable of containing the COVID-19 pandemic without substantially overloading ICU availability. Our results suggest that such overload could even be expected if all the 267 ICU beds in both private and public hospitals within the entire Eastern Cape Province would be exclusively available for critical COVID-19 patients in the Nelson Mandela Bay Municipality only.

Realistic or complete lockdown offer options of greatly reducing the pressure on the health care system if enacted rapidly enough. However, economic boundary conditions and in particular the large inequality in South Africa – and similarly in many other countries of the Global South – pose additional problems. Thus, in our opinion, in particular complete lockdown seems hardly enforceable and would appear unsustainable especially for a large share of people with lower income, as already weaker containment will likely lead to severe economic consequences in addition to disease related deaths[36,37].

How can the number of critical cases be confined given that the default scenario is already enacted? On April 9th, 2020, the number of cases reported in NMBM was 30[38]. As the number of reported cases seem to systematically underestimate their actual number by at least a factor of three, as predicted for Austria on April 10, 2020[10], we estimate that on 9th of April, at least 100 cases existed in NMBM and take that as our initial condition. Starting simulations with the default scenario active, we find that critical cases are likely to vastly exceed the available ICU capacity (Figure 3A) within two months. In contrast, introducing the realistic lockdown scenario immediately, i.e. starting April 13th, might support a successful confinement of the number of critical COVID-19 patients in NMBM to manageable numbers (Figure 3B). In this scenario, the simulations suggest that there is about 80% likelihood that ICU capacity becomes overloaded at some time and that ,if overload occurs, it will be relatively mild (factor of 2-3 of the capacity, in contrast to factor of about 30 when keeping the default measures as they are).

We remark that the success of such lockdown countermeasures crucially relies on several restrictions and our simulations likely under- rather than overestimate future case numbers. First in our simulations, activities are immediately reduced to the set low values (complete shutdown of public transport, child care and educational facilities, 90% reduction of all other activities) and all inhabitants fully comply with these restrictions. Second, our simulations are based on estimated parameters that thereby come with uncertainties, and stochastic dynamics may create large deviations from the predicted values, in particular also earlier growth and larger total number of critical patients, not last due to an exponential growth of

the outbreak in its initial phase without severe lockdown (compare[39]). Third, our estimates assume that all ICU beds would be available exclusively for COVID-19 patients during the entire time of the outbreak. Those and other constraints call for a more conservative, especially earlier introduction of realistic countermeasures.

We provide additional measures recorded from simulations on the location of infection events and exact values of the health care system overload in Tables 3 and 4, respectively.

Across all scenarios studied, the results thus indicate that it may be hard to enact realistic, socially and economically feasible countermeasures without exceeding ICU capacity and that more drastic measures beyond the current default are rapidly needed. Finally, it seems reasonable to assume that the consequences of countermeasures would be qualitatively the same across South Africa as well as many countries of the Global South.

Data availability
All data underlying the results are available as part of the article and no additional source data are required.

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Open Peer Review

Current Peer Review Status: ✗ ?

Version 1

Reviewer Report 05 October 2021

https://doi.org/10.5256/f1000research.31246.r93806

? **Theresa Marié Rossouw** (iD)

Department of Immunology, Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa

This is a well-conducted simulation of the impact of various COVID-19 containment options in the Nelson Bay Municipality in South Africa. While the article considers containment strategies at the beginning of the COVID-19 pandemic, it could still have important implications for public health measures aimed at containment of subsequent waves of the pandemic.

The title should be delimited since data from only one municipality (and not the entire South Africa) were used.

Reference 5 - World Health Organization: Q&A on COVID-19, HIV and antiretrovirals.2020 – does not seem appropriate for this statement: *"by April 2020 the World Health Organization (WHO) had confirmed[5] about 1.6 million cases worldwide"*.

"Consequently, the COVID-19 epidemic was declared a pandemic as it started to impact economies worldwide." - This sentence seems to suggest that a pandemic is declared when economies are impacted, but a pandemic is defined as "an epidemic occurring worldwide, or over a very wide area, crossing international boundaries and usually affecting a large number of people" Porta, M. *A Dictionary of Epidemiology* (Oxford University Press, USA, 2008).

"The significance of timely countermeasures could be seen in the development of infections in the United States, where cases surged from 1,678 to 307,318 between March 16, and April 6, 2020[6,7]." - This sentence seems to suggest that the United States had timely countermeasures in place, but this is not evident from the number of infections. Do the authors rather mean that the significance of the absence of timely countermeasures is evident in these figures?

The reference source of the following reference "World Health Organization: Global research on coronavirus disease (COVID-19). 2020" does not seem appropriate for the following statement: *"Most countries of the Global South were affected as well, often with reported case numbers just*

beginning to surge".

"current measures implemented in South Africa as of early April 2020[23]*. The reference is not freely available and the article is titled: "Fikile Mbalula relaxes Covid-19 regulations for taxi industry".* - Since it is difficult to see how the following facts could have been derived from this article, a different source should be considered (such as, Disaster Management Act: Regulations to address, prevent and combat the spread of Coronavirus COVID-19: Amendment) and an explanation of the percentage reductions should be provided: "These include the shutdown of childcare and educational institutions, the prohibition of leisure activities of any kind and cutting shopping activity options by about 70%. Moreover, work related and "other" activities (for example trips to health care facilities and visits to public institutions) and travelling as passenger in a car are reduced by 80% and formal and informal public transport is reduced by 30%."

Please amend the word "currently" so that it is clear that it refers to the situation during March/ April 2020 rather than at the present moment.

"Third, as a harsher variation of the lockdown that may be achievable in principle, we study the effect of a <u>realistic</u> lockdown scenario". - I do not think that the term "realistic lockdown" is the best one to use since the authors themselves state that this may not be achievable in practice, thus making it unrealistic. Would another term, such as "idealistic", "harsher" or "more restrictive", not be more appropriate?

"As scaling the capacity of minibus taxis to 1.5 passengers would strongly underestimate the infections during minibus taxi trips, several test scenarios with different fleet sizes and passenger capacities were carried out." - Since the restrictions operative during the time of the study was a limitation to 70% of capacity, did the authors specifically consider this scenario?

"Moreover, people with different places of work and residence mix up <u>at</u> this small space" – please change "at" to "in".

"Most of the contact intensities were left at their default since it is reasonable to assume that the contact intensities of most activities do not differ significantly from the values determined by[21]*".* - The reference provided is "Müller SA, Balmer M, Neumann A, *et al.*: Mobility traces and spreading of covid-19. *Technical report* Berlin: Technische Universität; 2020." This article is still a preprint despite being submitted on 30 March 2020. Are there no published articles to base the epidemic parameters on?

It is not clear where some of the epidemic parameters had been derived from. For instance, *"4.5% of all infected agents become seriously sick on day 10 and of these, 25% become critical the following day."* and *"Contagious agents recover 16 days after infection, whereas the infection of patients with severe conditions terminates after 23 days."* - Do the authors imply that patients with severe disease remain contagious up to 23 days? Appropriate references are important since many of these estimates have changed with the new variants.

"Across all scenarios enacted, outbreak dynamics also causes overload of the approximately ICU beds estimated as baseline for NMBM (Figure 1E,F)." - The colours for the "realistic lockdown" and "complete lockdown" scenarios are difficult to distinguish in these 2 figures. Also please explain that the same data are presented in the 2 figures but on a different scale.

"As a precondition for successful containment, lockdown needs to be implemented sufficiently early on (in particular less than 7 days after the first 100 infected, <u>not</u> the first 100 confirmed infected)." - It is not clear where this precondition comes from. It does not appear that any modelling is shown to support this statement.

"Out of the total 267 ICU beds available in (public and private) hospitals in the whole Eastern Cape Province (data from 2008,[32])" – from the reference article it seems that there were only 252 (and not 267) ICU beds in the Eastern Cape province in 2008. Since the data are very old, the authors should consider adding that these data are from the last national audit of ICU resources in South Africa.

"only about 50 would be available for critical cases from the NMBM (scaled proportional to the relative population counts in 2011[33,34])". - It would be useful for readers to see the calculations for this estimate. In addition would a more reputable resources, such as the National Government website , not be a more appropriate source of data than Wikipedia?

"The integral is taken over the entire time of simulation, 64 days after the 100 people are infected in NMBM." - Please explain why 64 days were selected since it seems to be 67 from the epidemic parameters: *"At the beginning of the simulation, 10 randomly selected agents (corresponding to 100 people) are initially infected. After 7 days of uncontrolled spread, various countermeasures are implemented. We consider the dynamics until the countermeasures are in effect for 60 days."*

Figure 3: It would be useful to name figures 3A and 3B as *default scenario* and *realistic lockdown scenario* (or whatever new name is selected) respectively.

Table 3: "KiGa" – please explain the meaning of this abbreviation.

Reference 10: Could the authors please re-look at the reference source since it lands on a search page.

Please be consistent with the use of capitals for the words Global North and Global South.

Please amend for clarity: "with many infected responding entirely asymptomatic".

Please be consistent with the use of United States and U.S.

Some of the same authors have also published an article[1] making use of the same methodology and should consider citing this article for the sake of transparency, unless they can argue that the methodology was significantly different?

I could not find the supplemental material that is referred to in the text.

Finally, with the benefit of hindsight, we now know that the ICU's were not as overwhelmed as predicted by the scenarios presented in this manuscript. The authors should consider and discuss the possible reasons for this.

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Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Infectious Diseases Immunology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 23 July 2021

https://doi.org/10.5256/f1000research.31246.r88528

✗ **Cliff C Kerr** (iD)

Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation, Seattle, WA, USA

The authors present an agent-based model of COVID-19 in Eastern Cape, South Africa, during the very early part of the epidemic (March - April 2020). They "predict" that the health system will be overwhelmed even with a strict lockdown. My main comments on the paper are (a) South Africa is towards the end of its third wave, so it is unclear what the significance of this analysis of the first wave is; (b) the predictions made by the model, though they were reasonable as of April last year, do not seem to closely match what actually happened.

Specific comments:

1. The introduction contains a number of statements that are now quite outdated (e.g. "The transmission of COVID-19 is currently thought to occur through direct inter-person droplet-based infections through coughing and sneezing").

2. The introduction discusses SIR models, but COVID is typically modeled as SEIR, and indeed the methods later refer to an incubation time, so it seems an SEIR model is being used.

3. It's unclear the extent to which long-distance travel contributes to COVID spread. Infection events tend to happen locally (e.g., at restaurants and in multi-generational houses). Thus, the modeling approach used is not obviously capturing the most important features of population contact networks.

4. Was it really the case in South Africa that private car travel reduced by 80% and public transport by 30%? In other countries, these proportions were roughly reversed.

5. The use of survey data from 2004 is likely to have some limitations, such as due to the growth Port Elizabeth has seen in that time (according to Wikipedia, by roughly a factor of 4, though that may not be a reliable source). Can you cross-validate with e.g. Google mobility data?

6. The authors state "Public minibus taxis are assumed to take an important role in the epidemic simulation". This is a reasonable assumption, but I do not think subsequent data support this (i.e., whether there is a statistically significant correlation between minibus use and infection rates, after controlling for population density).

7. Sources should be provided for the disease duration and severity parameters; ideally distributions, rather than point estimates, would be used. Similarly, the values of all parameters in Eq. (1) should be provided.

8. The epidemic dynamics shown in Fig. 1 seem to have much too short of a timescale, and do not reflect what actually happened. Data on cases, deaths, and (if available) hospitalizations should be plotted on these figures for comparison. For example, the first wave lasted roughly five times as long as that shown here. In addition, ICUs were never overwhelmed during the first wave[1].

9. The fact that the model predicted that South Africa would experience a much worse first wave than the UK, when in fact the opposite occurred, would benefit from further discussion.

10. The authors are encouraged to obtain review and validation of inputs and results by collaborating with an epidemiologist or other public health official who has local expertise in the Eastern Cape region.

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Is the work clearly and accurately presented and does it cite the current literature?

No

Is the study design appropriate and is the work technically sound?
No

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: COVID-19, epidemiology, mathematical modeling

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

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