Supplementary file

NCEM v4.0 (District Model): Supplementary information

This document provides a technical overview of the National COVID-19 Epi Model (NCEM) provincial model. The model described in this document is the district-level NCEM model, created by the South African COVID-19 Modelling Consortium. There is also a separate document, the NCEM Provincial Model Code Guide, that gives an overview of the structure of the model code for the Provincial Model; the district model code has a similar structure. If there are any queries regarding the model or the code, please contact us on: info@sacovid19mc.co.za.

Model equations

The model describes the temporal evolution of the following state variables:

Variable	Definition
S	number of susceptible individuals
E	number of exposed but not yet infectious individuals
I_A	number of asymptomatic individuals (infectious)
I_P	number of presymptomatic individuals (infectious)
I_M	number of mildly and moderately ill individuals (infectious)
I_{ST}	number of individuals who are or will become severely ill and will access treatment but are not yet hospitalised (infectious)
$I_{S\bar{T}}$	number of individuals who are or will become severely ill but will not access treatment (infectious)
H_1	number of severely ill individuals who are hospitalized in the general (non-ICU) ward
H_2	number of individuals who are work will be come critically ill currently in the general (non-ICU) ward
C_{V1}	number of individuals who are critically ill, will eventually die, and are currently in the ICU (ventilator resourced)
C_{V2}	number of individuals who are critically ill, will eventually recover, and are currently in the ICU (ventilator resourced)
$C_{\bar{V}1}$	number of individuals who are critically ill, will eventually die, and are currently in the ICU (not ventilated)
$C_{\bar{V}2}$	number of individuals who are critically ill, will eventually recover, and are currently in the ICU (not ventilated)
H_3	number of individuals who have been critically ill, will recover, and have been discharged from the ICU but remain in hospital for step-down care
W_H	number of severely ill individuals who have sought hospitalization but could not be accommodated
W_V	number of critically ill individuals who require a ventilator-resourced ICU bed but could not be accommodated
$W_{\bar{V}}$	number of critically ill individuals who require a non-ventilator-resourced ICU bed but could not be accommodated
R	number of individuals who are no longer infectious / recoverd and/or discharged

D	number of individuals who have died
I_{M_d}	cumulative number of *confirmed* mild / moderate infections
I_{S_d}	cumulative number of *confirmed* severe and critical infections
N	total number of individuals in the population ($S + E + I_A + I_P + I_M + I_{ST} + I_{S\bar{T}} + H_1 + H_2 + C_{V1} + C_{V2} + C_{\bar{V}1} + C_{\bar{V}2} + H_3 + R + W_S + W_V + W_{\bar{V}}$)
X	dummy variable representing mild and moderate cases who will be tested before they are tested
Y	dummy variable representing severe and critical cases who will be tested before they are tested

The following equations describe the dynamics of transmission and disease progression within each district, x:

$$\frac{dS_x}{dt} = -\Phi_x S_x$$

$$\frac{dE_x}{dt} = \Phi_x S_x - \gamma_1 E_x$$

$$\frac{dI_{A_x}}{dt} = p_a \gamma_1 E_x - r_1 I_{A_x}$$

$$\frac{dI_{P_x}}{dt} = (1 - p_a)\gamma_1 E_x - \gamma_2 I_{P_x}$$

$$\frac{dI_{M_x}}{dt} = p_{m_x} \gamma_2 I_{P_x} - r_2 I_{M_x}$$

$$\frac{dI_{ST_x}}{dt} = (1 - p_{m_x}) p_{t_x} \gamma_2 I_{P_x} - \tau_s I_{ST_x}$$

$$\frac{dI_{S\bar{T}_x}}{dt} = (1 - p_{m_x})(1 - p_{t_x})\gamma_2 I_{P_x} - r_8 I_{S\bar{T}_x}$$

$$\frac{dH_{1_x}}{dt} = \alpha_{1_x}\left(1 - \frac{p_{c_x}}{1 - p_{m_x}}\right)\tau_s I_{ST_x} - r_3 H_{1_x}$$

$$\frac{dH_{2_x}}{dt} = \alpha_{1_x}\frac{p_{c_x}}{1 - p_{m_x}}\tau_s I_{ST_x} - \tau_p H_{2_x}$$

$$\frac{dC_{V1_x}}{dt} = \alpha_{2_x} p_{v_x} d_{cv_x} \tau_p H_{2_x} - \mu_v C_{V1_x}$$

$$\frac{dC_{V2_x}}{dt} = \alpha_{2_x} p_{v_x}(1 - d_{cv_x})\tau_p H_{2_x} - r_9 C_{V2_x}$$

$$\frac{dC_{\bar{V}1_x}}{dt} = \alpha_{2_x}(1 - p_{v_x}) d_{c\bar{v}_x} \tau_p H_{2_x} - \mu_{\bar{v}} C_{\bar{V}1}$$

$$\frac{dC_{\bar{V}2_x}}{dt} = \alpha_{2_x}(1 - p_{v_x})(1 - d_{c\bar{v}_x})\tau_p H_{2_x} - r_{10} C_{\bar{V}2_x}$$

$$\frac{dH_{3_x}}{dt} = r_9 C_{V2_x} + r_{10} C_{\bar{V}2_x} - r_5 H_{3_x}$$

$$\frac{dR_x}{dt} = r_1 I_{A_x} + r_2 I_{M_x} + (1 - d_{s_x}) r_3 H_{1_x} + r_5 H_{3_x} + \left(1 - \frac{p_{c_x} d_{C\bar{T}}}{1 - p_{m_x}} - \frac{p_{s_x} d_{S\bar{T}}}{1 - p_{m_x}}\right) r_8 (W_{H_x} + I_{S\bar{T}_x})$$

$$\frac{dD_x}{dt} = d_{s_x} r_3 H_{1_x} + \mu_V C_{V1_x} + \mu_{\bar{V}} C_{\bar{V}1_x} + \left(\frac{p_{c_x} d_{C\bar{T}}}{1 - p_{m_x}} - \frac{p_{s_x} d_{S\bar{T}}}{1 - p_{m_x}}\right) r_8 (W_{H_x} + I_{S\bar{T}_x}) + r_9 W_{V_x} + r_{10} W_{\bar{V}_x}$$

$$\frac{dW_{H_x}}{dt} = (1 - \alpha_1)\tau_s I_{ST} - r_8 W_{H_x}$$

$$\frac{dW_{V_x}}{dt} = (1 - \alpha_2) p_{v_x} \tau_p H_2 - r_9 W_{V_x}$$

$$\frac{dW_{\bar{V}_x}}{dt} = (1 - \alpha_2)(1 - p_{v_x}) \tau_p H_2 - r_{10} W_{\bar{V}_x}$$

$$\frac{dX_x}{dt} = d_m p_{m_x} \gamma_2 I_{P_x} - \Delta_m X_x$$

$$\frac{dY_x}{dt} = \alpha_1 d_s \tau_s I_{ST_x} - \Delta_s Y_x$$

$$\frac{dI_{M_d}}{dt} = \Delta_m X_x$$

$$\frac{dI_{S_d}}{dt} = \Delta_s Y_x$$

where the force of infection, Φ_x, is defined as

$$\Phi_x = \frac{\beta_x \delta_{x,t} \left(\zeta I_{A_x} + \zeta I_{P_x} + I_{M_x} + I_{ST_x} + I_{S\bar{T}_x} + W_{H_x}\right)}{N_x}$$

and $p_{c_x} = 1 - p_{m_x} - p_{s_x}$.

Key parameter values

Tables 2 and 3 below show the values of key parameters used to inform the model. Parameter values have been selected for use by an expert panel of clinicians on the SA COVID-19 Modelling Consortium and updated with inputs from recent South African data where indicated. Parameter values that are provided as ranges only differ by province.

Table 1 Results of NICD analysis of estimated national and provincial reproductive numbers [1,3]*

Restriction level	**National**	**Eastern Cape**	**Gauteng**	**KwaZulu Natal**	**Western Cape**
None (R_0)	2.5 (2, 3)	2.5 (2, 3)	2.5 (2, 3)	2.5 (2, 3)	2.5 (2, 3)
Level 5 R_t[2]	1.3 (1.0, 1.6)	1.4 (1.1, 1.7)	1.2 (1.0, 1.4)	1.1 (0.9, 1.43	1.5 (1.2, 1.8)

Level 4 R_t: NICD R_t estimates calibrated to fit hospital-based provincial deaths[2]	1.6 (1.3, 1.9)	1.6 (1.2, 1.8)	1.8 (1.4, 2.2)	1.6 (1.3, 1.9)	1.6 (1.3, 1.9)
	Other Provinces	**Eastern Cape**	**Gauteng**	**KwaZulu Natal**	**Western Cape**
Level 3 (1–30 June): increase in contacts (relative to previous period) estimated from a decrease in residential mobility[3]	(21.1%, 26.0%)	21.0% (16.8, 25.2)	4.3% (3.4, 5.2)	20.5% (16.4, 24.6)	8.1% (6.5, 9.7)
Level 3 (1 July – 17 August): increase in contacts (relative to previous period) estimated from a decrease in residential mobility[3]	(0.5%, 2.5%)	3.0% (2.4, 3.6)	1.8% (1.4, 2.2)	0.8% (0.6, 1.0)	6.6% (5.3, 7.9)
Level 2 (18 August ->): increase in contacts (relative to previous period) estimated from a decrease in residential mobility[3]	(3.3%, 5.8%)	5.4% (4.3, 6.5)	1.7% (1.4, 2.0)	4.8% (3.8, 5.8)	3.1% (2.5, 3.7)

* We utilised national estimates where provincial data was too sparse. R_0, and R_t for Level 5 and Level 4 from symptom onset date adjusted for testing volumes

Table 3. Key model parameters

	Parameter	**Value (range)**	**Sources**
Infection severity	Proportion of cases that are asymptomatic	75% (70% - 80%)	[9-12]
	Relative infectiousness of asymptomatic cases	80% (77.5%, 82.5%)	[13-15] Estimated through calibration to admissions and fatalities count data (DATCOV) [4]
	Mild to moderate cases among the symptomatic	(94.55% - 97.13%)	Estimated through calibration to admissions and fatalities count data (DATCOV) [4]
	Severe cases among the symptomatic	(2.58% - 5.00%)	
	Critical cases among the symptomatic	(0.18% - 0.55%)	
	Fatal cases among the admitted (general)	(6.82% - 20.28%)	Estimated from NICD COVID-19 Hospital Sentinel Surveillance database (DATCOV) [4] & Western Cape Line List Data (SPV) [16]
	Fatal cases among the admitted (ICU ventilated)	(43.01% - 85.03%)	
	Fatal cases among the admitted (ICU non-ventilated)	(22.73% - 43.35%)	
	Proportion of cases in ICU requiring ventilation	(19.44% - 51.47%)	
	Fatal cases among the critically infected requiring ventilation, *in the absence of appropriate care*	100%	Expert opinion of clinicians convened by the National

	Fatal cases among the critically infected not requiring ventilation, *in the absence of appropriate care*	Unchanged: Fatal cases among the admitted (ICU non-ventilated)	COVID-19 Modelling Consortium
	Fatal cases among the critically infected requiring oxygen, *in the absence of appropriate care*	100%	
	Fatal cases among the severely infected requiring oxygen, *in the absence of appropriate care*	90%	
	Probability of seeking hospital-level care for severely and critically ill	(50.00% - 97.00%)	Estimated through calibration to 80% of excess mortality [5]
Timeframes & treatment durations	Time from infection to onset of infectiousness	2 days (1.0 - 3.0)	[8, 17-26] with input from the National COVID-19 Modelling Consortium
	Time from onset of infectiousness to onset of symptoms	4 days (3.0 - 5.0)	
	Duration of infectiousness from onset of symptoms	5 days (4.0 - 6.0)	[26, 27]
	Time from onset of symptoms to testing	4 days (3.0 - 5.0)	[17,18, 28-32]
	Time from onset of symptoms to hospitalisation	5 days (4.0 - 6.0)	
	Time in non-ICU (never ICU) to death/recovery	8 days (4.0 - 12·0)	Lengths of stay: values and ranges sourced from NICD COVID-19 Hospital Sentinel Surveillance database (DATCOV) [4]
	Time in non-ICU for those destined for ICU	0 days (0.0 - 2.0)	
	Time in ICU for those ventilated and destined to die	14 days (7.0 - 27.0)	
	Time in ICU for those never ventilated and destined to die	11 days (7.0 - 18.0)	
	Time in ICU for those ventilated and recovered	19 days (15.0 - 37.0)	
	Time in ICU for those never ventilated and recovered	5 days (1.0 - 10.0)	
	Time in non-ICUs for those who were in ICU and recovered	0 days (0.0 - 6.0)	

* A full list of parameters are available in the code.

Basic reproduction number

The expected number of secondary infections produced by a single infection introduced into a naive population (basic reproduction number) can be calculated as:

$$R_{0_x} = \beta_{x,0}\left(\frac{p_a\zeta}{r_1} + \frac{(1-p_a)}{\gamma_2} + \frac{(1-p_a)p_{m_x}}{r_2} + \frac{(1-p_a)(1-p_{m_x})}{\tau_s} + \frac{(1-p_{t_x})(1-p_a)(1-p_{m_x})}{r_8}\right)$$

In this context, a 'naive' population is the population at the start of the epidemic when (a) there are no previously-infected individuals ($S_x \approx N_x$) and (b) there are no measures or practices in place that reduce the contact rate below baseline ($\delta_{x,0} = 1$). We further assume that at this stage in the epidemic there will be hospital beds available for all severe and critical cases that access care ($\alpha_1 = 1$).

Time-varying reproduction numbers

The reproduction number is assumed to vary over time, reflecting changes in the contact rate that result from both government-enforced and individually-enacted measures. We refer to two types of time-varying reproduction numbers: $R_c(t) = \delta_t R_0$ denotes the hypothetical reproduction number at a given point in time that would be observed in the absence of previously-infected individuals, where δ_t is a proportional reduction from baseline; $R_e(t) = R_c(t)S(t)/N(t)$ denotes the realized reproduction number at a given point in time, taking into account accumulation of infection and immunity in the population.

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