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Estimating surge in COVID-19 cases, hospital resources and PPE demand with the interactive and locally-informed *COVID-19 Health System Capacity Planning Tool*

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Abstract

Introduction

The COVID-19 pandemic revealed an urgent need for analytic tools to help health system leaders plan for surges in hospital capacity. Our objective was to develop a practical and locally informed Tool to help explore the effects of public health interventions on SARS-CoV-2 transmission and create scenarios to project potential surges in hospital admissions and resource demand.

Methods

Our Excel-based Tool uses a modified S(usceptible)-E(xposed)-I(nfected)-R(emoved) model with vaccination to simulate the potential spread of COVID-19 cases in the community and subsequent demand for hospitalizations, intensive care unit beds, ventilators, health care workers, and personal protective equipment. With over 40+ customizable parameters, planners can adapt the Tool to their jurisdiction and changes in the pandemic.

Results

We showcase the Tool using data for Ontario, Canada. Using healthcare utilization data to fit hospitalizations and ICU cases, we illustrate how public health interventions influenced the COVID-19 reproduction number and case counts. We also demonstrate the Tool's ability to project a potential epidemic trajectory and subsequent demand for hospital resources. Using local data, we built three planning scenarios for Ontario for a 3-month period. Our worst-case scenario accurately projected the surge in critical care demand that overwhelmed hospital capacity in Ontario during Spring 2021.

Conclusions

Our Tool can help different levels of health authorities plan their response to the pandemic. The main differentiators between this Tool and other existing tools include its ease of use, ability to build scenarios, and that it provides immediate outcomes that are ready to share with executive decision makers. The Tool is used by provincial health ministries, public health departments, and hospitals to make operational decisions and communicate possible scenarios to the public. The Tool provides educational value for the healthcare community and can be adapted for existing and emerging diseases.

Keywords

epidemiology; health policy; infectious diseases; public health; statistics and research methods; COVID-19; interactive tool; health system capacity; predictive modeling; hospital bed demand; PPE demand

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Introduction

The Coronavirus Disease 2019 (COVID-19) pandemic has put unprecedented pressure on healthcare systems in Canada [1] and around the world [2]. Health leaders have sought models to provide short- and long-term forecasts of COVID-19 cases [3–5], demand for hospital resources [5–7], and the potential impact of public health interventions [5, 8, 9]. Many analytical models have been developed [5, 6, 10–12] to help decision makers plan for the pandemic. However, they are predominantly based on sophisticated software packages and require advanced knowledge and technical skills to use. To meet the planning needs of hospital managers, public health units and provincial health ministries in March 2020, we started developing the *COVID-19 Health System Capacity Planning Tool* (referred to as the Tool) with flexible and user-friendly features. By simulating the impact of various public health interventions, the Tool models SARS-CoV-2 transmission in the population and provides scenario-based projections for acute and critical care beds, ventilators, health care worker (HCW) staffing, and personal protective equipment (PPE) needed to care for patients with COVID-19. Designed for users with different levels of knowledge, the Tool uses the same underlying mathematical models as most other tools, but is Excel-based with parameter inputs, data outputs, and visualizations that are simple to understand, modify, and adapt to local contexts.

The impact of COVID-19 has been felt across Canada, but provinces and territories have experienced differences in disease burden, timing, and number of waves, and in the implementation of policies to prevent the spread of the virus [13, 14]. Our Tool contains over 40 customizable parameters, enabling decision-makers at all levels to create local scenarios and plan for surges in health resource demands and supply shortfalls associated with the COVID-19 pandemic in their region. The Tool has been used successfully by provincial health ministries, public health departments and hospitals across Canada to make operational decisions and inform the public about potential scenarios. The Tool continues to evolve to reflect changes in our understanding of SARS-CoV-2 transmission as new variants of concern (VOCs) emerge and vaccination rollouts offer hope in defeating this virus.

In the following sections, we present our underlying methodology, data sources and parameters, and results by applying the Tool to data from Ontario, Canada. Ontario is Canada's largest province, has the country's largest number of confirmed COVID-19 cases [13], and has easily accessible COVID-19 data.

Methods

Tool development and framework

During the early stage of the pandemic, our team engaged and exchanged information with the Public Health Agency of Canada, ministries of health, modelling experts in the academic community, hospitals, regional health authorities, and public health units to develop and shape this Tool. For modelling transparency, simplicity and ease of use, we implemented the Tool in Microsoft Excel. It is available to potential users upon request by contacting the Canadian Institute for Health Information (help@cihi.ca).

The *COVID-19 Health System Capacity Planning Tool* covers the major aspects of COVID-19 health capacity planning in one model, from forecasting epidemic trajectories to hospital bed supply and demand to PPE and staffing needs. Our Tool has three interconnected modules: the Epidemiological (Epi) module, Capacity module and HCW/PPE module (Figure 1, detailed description provided in Appendix A1). The Epi module simulates the potential spread of COVID-19 cases, considering local public health measures, transmissibility, and vaccination rates. The Capacity and HCW/PPE modules estimate hospital resources and the number of healthcare workers and PPE required to treat COVID-19 patients, respectively.

Model

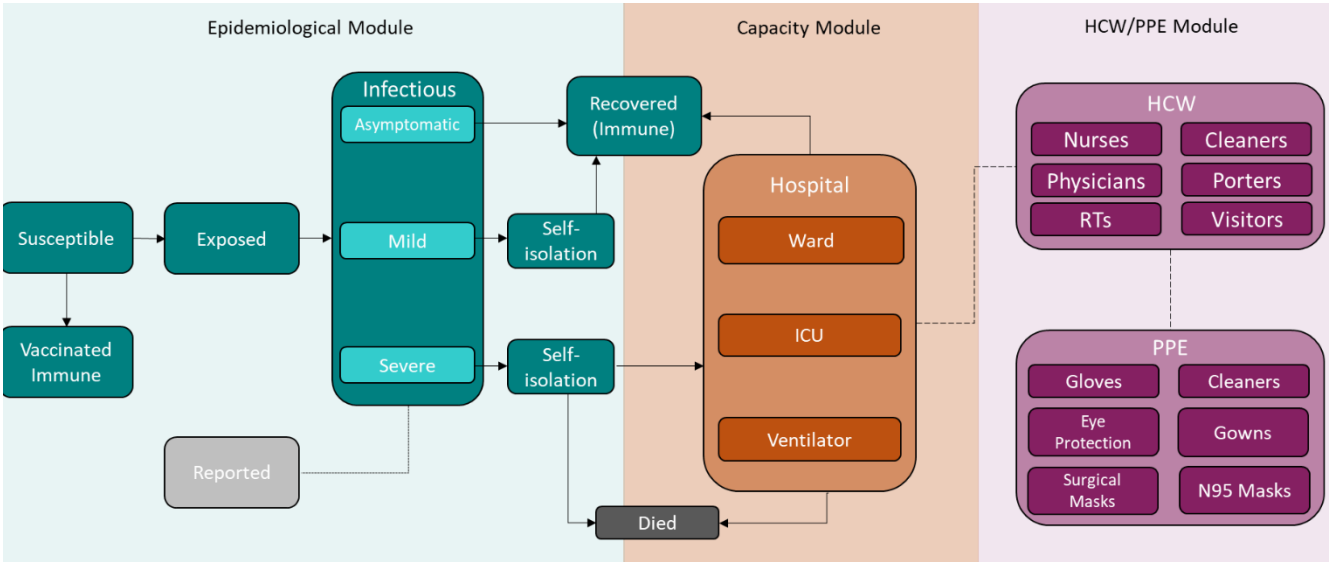
Epi module

The Epi module simulates the potential spread of COVID-19 cases in a previously unexposed population. This module requires users to input locally derived data such as cumulative COVID-19 cases, population size, dates of public health measures, and vaccination rates.

The Epi module was built using a modified version of the Susceptible-Exposed-Infected-Removed-type deterministic compartmental model with vaccination [15–18]. To implement this model in Excel we used a discrete-time version of the model [19]. The Epi module in Figure 1 (teal box) illustrates how individuals in the population move across compartments according to the stages of COVID-19 progression. For example, someone could be susceptible to infection, an asymptomatic infectious case, recovered, etc. In addition to S-E-I-R classes, we included a *Reported* compartment to capture the reporting delay [20] between an individual being exposed to the virus and reported as a case. By customizing the reporting delay and proportion of COVID-19 cases reported, planners can reflect local testing guidelines. We also created a *Vaccination* compartment to examine the impact of vaccination rollouts [21]. The vaccination component is implemented as a step function where the daily vaccination rate, vaccine efficacy, and the delay for the vaccine to be effective can be modified for different time periods. Table 1 contains a list of key epidemiological parameters and values (full list is provided in Appendix Table A2.2, model equations can be found in Appendix Table A2.3).

Disease transmission varies between regions and over the course of the pandemic because of factors such as the initial rate of disease spread, local contact rate, demographics, population density, and public health interventions, among others [27]. The changing COVID-19 transmission is captured in our model with a dynamic effective reproduction number, $R_{eff}(t)$, using a time-varying piecewise function. $R_{eff}(t)$ is estimated in the Tool by fitting the modeled reported cases to the local observed cumulative cases (Figure 2). By creating the timeline of interventions and finding the appropriate model fit, the planner can study the effects of various public health strategies on the changes in $R_{eff}(t)$ and community transmission as shown in the example in the Results section.

Figure 1: Flowchart for the *COVID-19 health system capacity planning tool*



Abbreviations: HCW; health care worker, PPE; personal protective equipment, RT; respiratory therapist.
The Tool includes three modules: the Epidemiological (Epi) module (teal), the Capacity module (orange) and the HCW/PPE module (purple). Each module consists of multiple compartments (boxes) that represent COVID-19 disease states in the Epi and Capacity modules, and supply categories in HCW/PPE module. Arrows with solid lines show the flow of individuals in the population between compartments in the Epi and Capacity modules. The dotted line for the Reported compartment indicates that not every case is reported and that there is a delay between the time of exposure and the case being reported. The dashed arrows between the Capacity and HCW/PPE modules represent the flow of information rather than individuals.

Table 1: Key epidemiological parameters

Parameter	Definition	Value	Reference
Latent period, $1/\sigma$	The period between the point of infection and the onset of infectiousness (based on 5.1 days incubation period, i.e., from the point of infection to symptoms onset and a 1-day pre-symptomatic infectious period)	4.1 days	Lauer et al. (2020) [22], He et al. (2020) [23]
Infectious period for asymptomatic cases, $1/\gamma_A$	The period between onset of infectiousness and recovery for someone who is asymptomatic	6 days	Hu et al. (2020) [24]
Infectious period for mildly symptomatic cases, $1/\gamma_{SM}$	The period between the onset of infectiousness and self-isolation for someone who develops mild symptoms	4 days	Li et al. (2020) [25]
Infectious period for severely symptomatic cases, $1/\gamma_{SS}$	The period of infectivity for someone who develops severe symptoms	4 days	Assumed to be the same as the infectious period for the mild cases
Percentage of asymptomatic cases, P_A	Percentage of persons who are infected with SARS-CoV-2 but never show symptoms of the disease.	33%	Oran et al. (2021) [26]

Note: Parameters can be adjusted by the user to reflect local information, if available, as well as the latest scientific evidence.

Capacity module

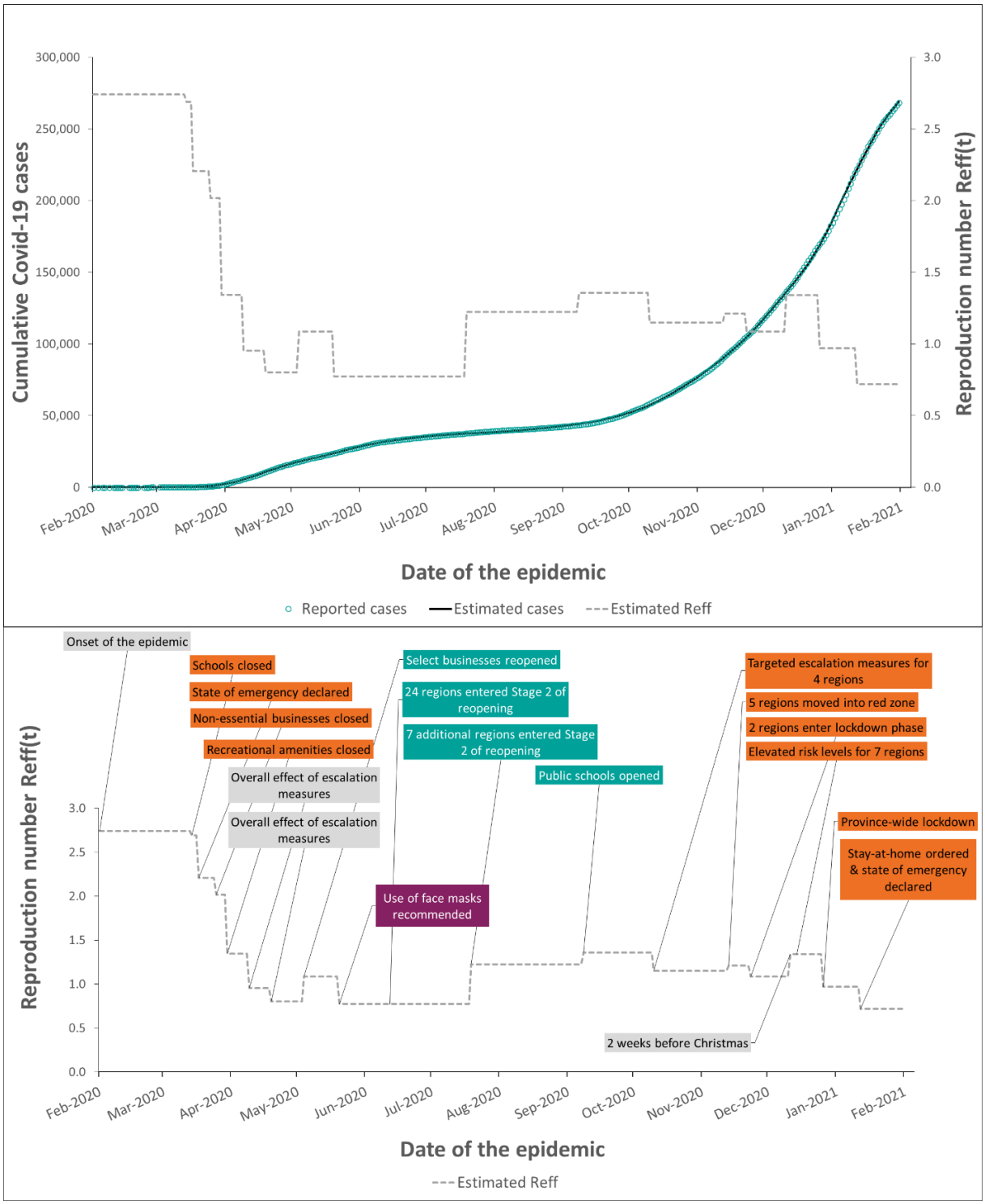
The Capacity module estimates the hospital resources required to treat COVID-19 patients. The model is an extension of the Epi module and is split into three compartments representing the hospital environment: *Ward* accounts for non-critical care inpatient beds; Intensive Care Unit (*ICU*) represents critical care beds without ventilation; and *Ventilator* signifies ICU beds with invasive mechanical ventilation (Figure 1). Hospital resource capacity is also included as an input to the model to estimate the potential date when resources may be depleted and to quantify the gap between bed capacity and demand.

This module requires users to input locally derived clinical administrative data such as statistics on health care usage and deaths (Table 2), which have changed dramatically across Canadian jurisdictions over the course of the pandemic [29]. The proportion of cases hospitalized and their LOS have changed throughout the pandemic due to the circulation of new variants. Our model allows planners to input multiple sets of health system usage parameter values, making this component highly customizable to each jurisdiction where the timing of changes in health care utilization might differ.

HCW/PPE module

The HCW/PPE module estimates the number of health care workers (i.e., physicians, nurses and other clinical and hospital

Figure 2: Estimated $R_{eff}(t)$ and potential effect of control measures in Ontario, Canada



The top panel shows the reported cumulative cases (teal circles) versus the modelled cases (solid line) for Ontario, Canada from 1st February 2020 to 31st January 2021. Model fit: MAPE = 0.8%. The estimated time-dependent reproduction number, $R_{eff}(t)$, is plotted as a dashed line. The bottom panel shows a timeline of public health measures that coincide with changes in $R_{eff}(t)$.

support staff) and PPE required to care for COVID-19 patients in inpatient acute-care settings (Figure 1). The formulas to calculate healthcare worker demand are based on the average number of active daily COVID-19 patients in each acute-care setting and information on staff-patient interactions including contact frequency, the number of contacts per patient per shift, shift length, and the staff-to-patient ratio in that setting.

PPE usage is calculated for each type of healthcare worker based on the number of each type of equipment required and whether this is per shift (as in the case of eye protection or gowns) or per patient contact (as in the case of disposable gloves) [30]. The default values for PPE usage were obtained from the World Health Organization [31] and from interviews with clinicians in Ontario and Newfoundland (see Appendix

Table 2: Parameter values related to healthcare usage and deaths

Parameter	1st February 2020–31st March 2020	1st April 2020–31st May 2020	1st June 2020–31st July 2020	1st August 2020–30th September 2020	1st October 2020–30th November 2020	1st December 2020–31st January 2021
Percentage of hospitalizations (calibrated), %$^{\perp}$	19.0	11.6	2.0	2.7	3.4	4.1
Percentage of hospitalizations (baseline), %$^{\perp\perp}$	11.3	12.5	10.5	3.8	3.5	4.0
Percentage of ICU admissions (among hospitalized cases), %°	33.9	22.9	21.8	24.3	32.5$^{\perp}$	30.5$^{\perp}$
Percentage of ICU admissions with mechanical ventilation, %°	75.7	64.7	51.1	45.1	33.6$^{\perp}$	42.5$^{\perp}$
Average LOS in ward (non-fatal cases), days°	22.86	23.07	14.27	12.66	12.66*	12.66*
Average LOS in ward (fatal cases), days°	32.70	13.74	24.48	21.98	21.98*	21.98*
Average LOS in ICU w/o ventilation (non-fatal cases), days°	5.30	5.00	6.20	5.50	5.50*	5.50*
Average LOS in ICU w/o ventilation (fatal cases), days°	4.80	3.40	5.50	5.80	5.80*	5.80*
Average LOS in ICU with ventilation (non-fatal cases), days°	25.10	26.40	30.20	18.60	18.60*	18.60*
Average LOS in ICU with ventilation (fatal cases), days°	14.00	16.90	17.70	22.10	22.10*	22.10*
Percentage of deaths among non-critical cases (ward only), %°	15.2	23.4	10.6	12.7	12.7*	12.7*
Percentage of deaths among cases admitted to ICU w/o ventilation, %°	19.5	23.9	16.5	11.5	11.5*	11.5%*
Percentage of deaths among cases admitted to ICU with ventilation, %°	35.5	46.5	44.2	51.7	51.7*	51.7*

Abbreviations: ICU, intensive care unit; LOS, length of stay; w/o, without.

$^{\perp}$These values were calibrated from the Ontario baseline values based on the model best fit (MAPE for cumulative reported cases = 0.8%, MAPE for hospitalizations = 8.5%, MAPE for ICU admissions = 12.8%, MAPE for ICU admissions with ventilation = 18.4%, see also Figure).

$^{\perp\perp}$The baseline values for the percentage of cases hospitalized were estimated as the percentage of "total confirmed cases" "ever hospitalized" for the reported period from the daily epidemiologic summaries from Public Health Ontario [28]. Detailed calculations are presented in Appendix Table A2.4. Note that the percentage of cases hospitalized cannot be accurately determined from the existing data as there is no linkage between the testing data and the hospitalization data.

° Based on the detailed information on acute care hospitalizations for patients with a diagnosis of COVID-19 in CIHI's COVID-19 Hospitalization and Emergency Department Statistics, 2019–2020 and 2020–2021 [29]. Detailed COVID-19 episode of care breakdowns for modelling, by recipient province/territory and admission month, DAD, January to November 2020" Table.

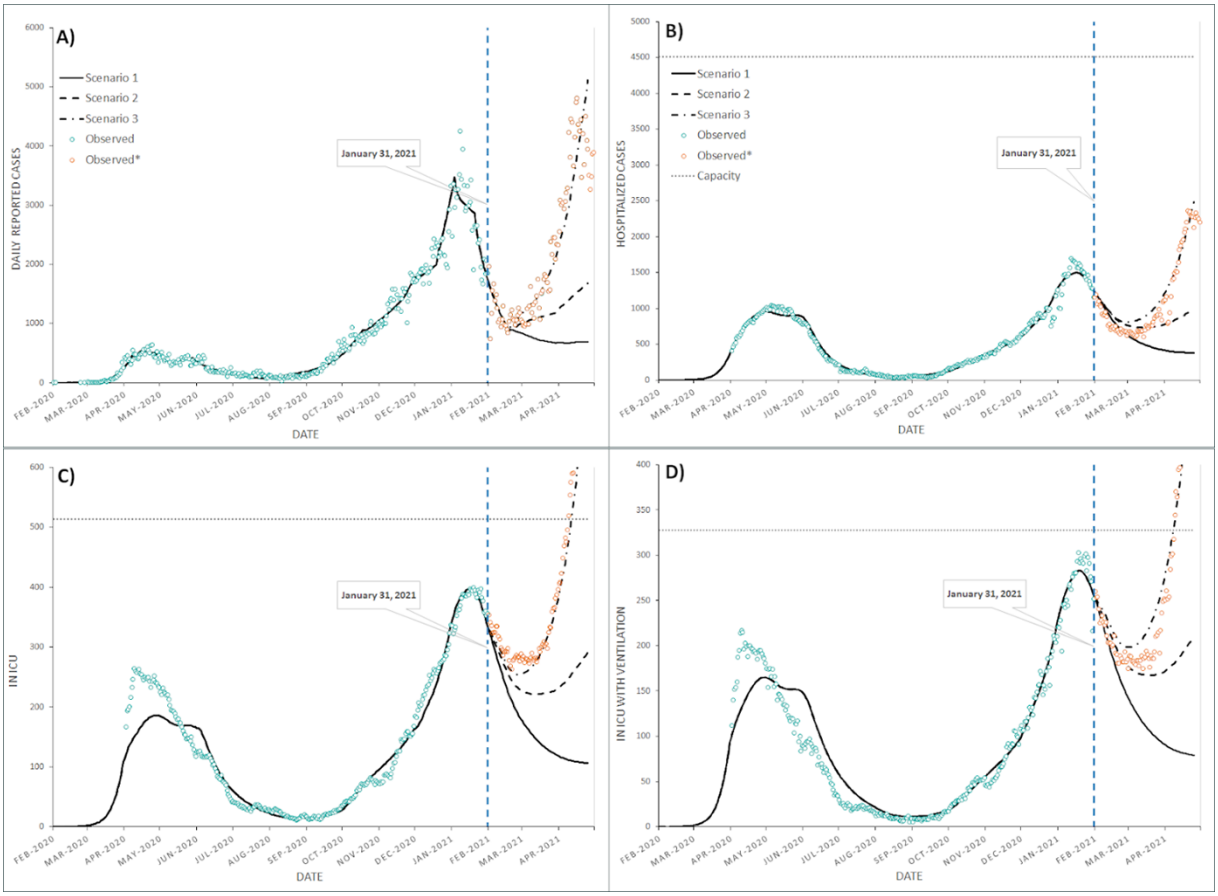
*The values for LOS and fatality rates for the 1st October 2020–30th November 2020 and 1st December 2020–31st January 2021 time periods were assumed to be the same as for the 1st August 2020–30th September 2020 period. While the parameters from the DAD data were available up to 30th November 2020, the last period couldn't be included in the analysis, as a significant proportion of cases hospitalized from 1st October 2020–30th November 2020 are discharged after 30th November 2020 and will not be included in the reported data.

Tables A2.5 and A2.6 for default values). Users can alter these values to reflect the reality of their jurisdiction or organization.

Model validation

We validated the Tool results against two benchmarks. First, an internal validation was done to ensure that outputs produced by the model aligned with historical case, hospitalization, ICU admissions, and ICU admissions with ventilation data (Figure 2 and Figure 3, more details can be found in Appendix Tables A3.3.1 and A3.3.2). Second, we compared outputs from the model with case and hospitalization estimates generated by other major models (the McMaster Pandemic model [31], the online Epidemic

Figure 3: Scenario-based projections in Ontario, Canada (A) Daily number of reported COVID-19 cases (B) Hospitalized cases (C) Patients in ICU (D) Patients in ICU with ventilation. The model was fitted and calibrated (solid black line) to the historical data (teal circles) from 1st February 2020 until 31st January 2021



The three scenarios were produced for February to April 2021 (solid, dashed and dash-dotted black lines). The orange circles show the observed data from February to April 2021.

Calculator [32], University of Pennsylvania's CHIME PPE Calculator Excel application [33], and COVID-19 Modeling Collaborative's PPE Resource estimator [34]) and obtained very similar outputs, with no statistical differences across the models (see Appendix A3 for details).

For quality assurance of the Excel implementation, formulas and results were verified with a Python version of the model.

In the Tool, model fit is evaluated by the root mean square error (RMSE) [35]. The dynamic effective reproduction number (described below) values that minimize RMSE are obtained by utilizing Excel's Solver add-in [36] with nonlinear optimization using the Generalized Reduced Gradient method [37]. In this paper, we report the Median Absolute Percentage Error (MAPE), which, despite some limitations, is scale-independent and a more easily interpretable measure of the prediction accuracy of a projection [38, 39].

Results

For illustrative examples presented in this section, we use publicly available data for Ontario, Canada on daily cumulative cases [40], daily [40], and cumulative hospitalizations [28], ICU cases, ICU cases with mechanical ventilations [40], and population estimates [41]. For the dates of public health measures, we utilized the COVID-19 Intervention Scan Tool [42] and public announcements. Healthcare usage data were obtained from recent COVID-19 hospitalization statistics published by the Canadian Institute for Health Information [29].

In our first example, we used Ontario data from 1st February 2020 to 31st January 2021 to analyse the effects of various intervention policies on the reproduction number. In the second example, we illustrate how this Tool can be used to build scenarios to project the potential demand for hospital, HCW, and PPE resources using historically available data.

Observed impact of public health interventions

We created a timeline of major public health measures implemented in Ontario from 1st February 2020 to 31st January 2021 (Figure 2(B) and Appendix Table A2.7). We then estimated changes in $R_{eff}(t)$ for this period by fitting our model to the reported cumulative cases. We also validated these estimates by comparing them with the $R_{eff}(t)$ reported by Ontario (See Appendix Figure A3.4).

The number of reported cases in Ontario grew from 2 cases on 1st February 2020 to 268,211 cases on 31st January 2021. During the same period, $R_{eff}(t)$ fluctuated, as shown in the top panel of Figure 2. At the beginning

Table 3: Projection scenarios

		Scenario 1	Scenario 2	Scenario 3
Potential changes in $R_{eff}(t)$				
Public health announcements	**Date (2021)**	**$R_{eff}(t)$**	**$R_{eff}(t)$**	**$R_{eff}(t)$**
3 regions to reopen [44]	10th February	0.9	1.0	1.1
Additional 27 regions to reopen [53]	16th February	0.95	1.1	1.2
Additional 3 regions to reopen [54]	8th March	1.0	1.1	1.3
Further lifting of restrictions [55]	21st March	1.05	1.2	1.4
Potential further lifting of restrictions	1st April	1.1	1.2	1.5
Potential changes in hospital usage parameters				
Percentage of cases requiring hospitalization, %	1st February–30th April	4.1	5	5
Percentage admitted to ICU among those hospitalized, %	1st February 1–30th April	30.5	32.5	34.5
Percentage of ICU admissions with mechanical ventilation, %	1st February–30th April	42.5	44.5	46.5
Potential vaccine rollouts [56]				
Daily vaccination rate*	January	2,200	2,200	2,200
Daily vaccination rate*	February	6,900	6,900	6,900
Daily vaccination rate**	March	45,000	45,000	45,000
Daily vaccination rate**	April	90,000	90,000	90,000
Capacity available for patients with COVID-19				
Hospital beds	1st February–30th April	4,514	4,514	4,514
ICU beds	1st February–30th April	514	514	514
Additional 500 "surge beds"	February	1,014	1,014	1,014
ICU beds with ventilator	1st February–30th April	328	328	328

*Number of daily fully vaccinated individuals (i.e., 2 doses with 95% efficacy after 12 days)
**Number of daily vaccinated individuals with a single dose (i.e., 1 dose with 70% efficacy after 12 days)

of the pandemic when no preventative measures were in place, $R_{eff}(t)$ was estimated to be 2.8. It started to decline to ~0.8 after various escalation measures were implemented including a declaration of a state of emergency, school and business closures, social distancing rules. The re-opening in May 2020 and the lifting of restrictions seemed to be associated with a slow growth of the reproduction number (and therefore transmission), which reached a value of 1.4 in September 2020. The recommendation of wearing face masks announced on 20th May, 2020 [43] seemed to have been associated with a reduction in the R_{eff}. New restrictions were implemented in some regions at the beginning of October 2020 to slow transmission, resulting in R_{eff} that fluctuated around 1 in October-November 2020. In December 2020, the R_{eff} increased again to about 1.3, which coincided with increased social interaction before and during the Christmas holidays. Following a second province-wide lockdown and stay-at-home orders, transmission decreased, and R_{eff} was estimated to be 0.7 at the end of January 2021.

Projected COVID-19 patterns and need for hospital resources

In our second example, we created three scenarios to project demand for healthcare resources for a three-month period, from 1st February 2021 to 30th April 2021 (Table 3, Figure 3) based on historical data presented in the previous example and reopening plans announced in February by the Ontario government [44]. The Tool can be applied in a similar manner to build projections for upcoming months with more recent historical data and current public health measures.

When building our scenarios, we focused on adjusting five parameters: $R_{eff}(t)$, which reflects changes in contact rate and viral transmissibility; hospitalization, ICU and ventilation rates, which vary depending on the virulence of circulating VOCs; and the daily vaccination rate, which changes over time and impacts the proportion of the population susceptible to infection and therefore the epidemic curve.

We proposed three scenarios. First, we projected the expected outcomes in a situation where the announced measures of reopening lead to a slight increase in population mobility and person-to-person contact. As a result, in this most optimistic scenario, Scenario 1, $R_{eff}(t)$ was assumed to increase very slightly. In contrast, the two more plausible scenarios represent situations where $R_{eff}(t)$ is assumed to increase by a magnitude like that during the reopening phase of the second wave of the pandemic in Ontario (Scenario 2) or even faster (Scenario 3) due to the higher transmissibility of emerging VOCs [45, 46]. When limited information about emerging VOCs exists, we can only make assumptions on how contagious or virulent they are in comparison with the dominant variant. Since there was early evidence of the Alpha variant (B1.1.7 VOC) being more transmissible and causing more severe illness than earlier variants, we assumed higher transmissibility, hospitalization, ICU and ventilation rates [47, 48] in Scenarios 2 and 3.

Table 4: Healthcare usage projections

Projected values for 1st May 2021	Scenario 1	Scenario 2	Scenario 3
Daily reported cases	690	1,764	5,997
Hospitalized cases	379	1,046	2,963
In ICU	105	307	930
In ICU with ventilator	78	223	650

Abbreviations: ICU, intensive care unit.

Table 5: Estimated weekly PPE usage

Week end date	COVID-19 patients hospitalized		Gloves (pair)		Eye protection		Surgical masks		N95 masks		Gowns	
Scenario	1	3	1	3	1	3	1	3	1	3	1	3
3/07/2021	588	815	44,660	63,441	8,777	12,576	5,699	7,544	6,840	10,578	8,777	12,576
3/14/2021	525	853	39,868	66,541	7,836	13,188	5,074	7,875	6,122	11,135	7,836	13,188
3/21/2021	476	928	36,198	72,554	7,111	14,365	4,605	8,573	5,554	12,131	7,111	14,365
3/28/2021	440	1,050	33,467	82,083	6,570	16,234	4,263	9,703	5,120	13,686	6,570	16,234
4/04/2021	414	1,226	31,526	95,937	6,182	18,951	4,023	11,352	4,803	15,942	6,182	18,951
4/11/2021	398	1,474	30,291	115,411	5,934	22,774	3,875	13,671	4,591	19,115	5,934	22,774
4/18/2021	391	1,821	29,728	142,663	5,816	28,126	3,813	16,918	4,481	23,562	5,816	28,126
4/25/2021	390	2,270	29,609	177,749	5,787	35,030	3,809	21,115	4,438	29,287	5,787	35,030
5/02/2021	391	2,802	29,725	219,163	5,805	43,192	3,835	26,088	4,433	36,047	5,805	43,192

Table 6: Estimated COVID-19 monthly patient staff requirements

Month	COVID-19 patients		Nurses (Ward)		Nurses (ICU)		Physicians (Ward)		Physicians (ICU)		Respiratory therapists		Cleaners		Porters	
Scenario	1	3	1	3	1	3	1	3	1	3	1	3	1	3	1	3
2021–02	891	961	216	226	490	566	43	45	49	49	1	1	244	279	3	4
2021–03	499	936	119	213	285	597	24	43	28	28	1	2	141	282	2	6
2021–04	395	1,922	95	438	222	1,213	19	88	22	22	0	4	105	547	2	14

For all scenarios, the vaccination rates for January to February 2021 represent the number of fully vaccinated individuals in Ontario [49] with 95% efficacy [21]. For the period of March to April 2021, we assumed that only a single dose vaccine was administered with 70% efficacy [49]. This is reflective of the changes in Canada's national vaccination strategy in Spring 2021, which aimed to maximize single dose immunizations and extend the interval for the second dose by up to four months [49].

Our worst case, Scenario 3, projected almost nine times the number of daily cases projected by Scenario 1 (5,997 vs. 690 on 1st May 2021). In Scenario 3, the projected ICU bed and ventilator demand surpassed the numbers that were available for COVID patients (Tables 3 and 4). However, the additional 500 ICU beds announced by the Ontario Government on 19th January 2021 [50] could provide adequate resources to care for this potential increase in hospitalized cases. As highlighted in Tables 5 and 6, estimated demand for PPE and health care staffing needs were also significantly higher for Scenario 3.

We then compared our projected scenarios with the cases and hospitalizations observed from February to April in Ontario (Figure 3, orange dots). As shown in our worst-case projections (Scenario 3), without enhanced public health measures and with several Ontario hospitals already at or over capacity in February [50], the rise in COVID hospitalizations reached the ICU bed capacity in April 2021 [51, 52]. As illustrated by this example, the scenario comparison can be a useful tool to help policy makers estimate risks and take actions to reduce new infections and ultimately, hospitalizations and fatalities.

Discussion

We developed a tool that can assist various levels of health care planners in making short- and long-term decisions about healthcare capacity, PPE, and healthcare workforce needs. Used alongside other models and information (e.g., financial, ethical, etc.) it could aid planners when weighing decisions related to COVID-19. Different jurisdictions and regions experience differences in intensity and timing of outbreaks [57], presence of VOCs [58] and severity of cases [29], implementation of public health measures [42] and vaccination strategies [59]. These local specifics can be simulated by our Tool with its highly customizable parameters that rely on local data inputs.

Our examples from Ontario, Canada illustrate how a planner could apply the Tool to a particular context given the current state of events, local case, hospital, healthcare workforce, supply chain data, and evolving information about emerging VOCs. The coronavirus changes very rapidly due to the high number of mutations [60]. As we witnessed with the current VOC, Omicron, viral transmissibility and disease severity can drastically change from one variant to the next [61]. These factors can be reflected by adjusting parameters in the Tool, making it highly adaptable to new VOCs.

Many local [5, 62–67] and national [7, 9, 68, 69] Canadian models and tools [11, 12, 70, 71] were developed to assist jurisdictional authorities and hospital planners with pandemic preparedness. Often these models require a high level of understanding of the underlying mathematical modelling techniques, proficiency in a specific software program and a team of modellers to build projections, maintain and update the model [6, 10–12]. In contrast, existing online tools [70, 71] are relatively simple to use but cannot easily reflect the rapidly changing situation due to the use of static parameters and cannot fit the model to the observed data. Our Tool was designed with our end-users in mind; the Excel implementation, user-friendly outputs, and visualizations make the Tool easy to apply by planners with different levels of knowledge. It also includes several time-varying parameters such as $R_{\text{eff}}(t)$, which enables the simulation of multiple waves, and hospital usage parameters, which changed significantly over time. We also periodically update the Tool and parameters with the most recent information and user feedback.

The impact of the Tool has been significant. Federal and provincial public health agencies and health ministries, public health units, academics, and hospitals across the country have used it for a variety of purposes including updates to executive teams and government officials, validation of projections produced by other models, and within local dashboards for operational planning. The Government of Newfoundland and Labrador [72] and Toronto Public Health [73] have used the Tool to generate scenarios used in public releases and highlight the importance of public health measures to curb viral transmission. Our Tool continues to evolve and inform health care planning. We continue to engage stakeholders in methodological and policy discussions to understand their health resource planning and pandemic preparedness needs and help them apply the Tool to create realistic local scenarios.

Limitations

Our model, as with any deterministic SEIR-type model, has several limitations [74]. The main assumption of the model, a homogeneous well-mixed population, ignores the fact that most contacts with COVID-19 cases occur not at random but within groups of people in social or geographical proximity [75]. The model works well when simulating outbreaks in large, well-mixed populations rather than in small populations (e.g., small town or long-term care facility), where stochastic effects are much more profound and agent-based type models are more suitable [76]. Our model does not account for differences in susceptibility to COVID-19 with respect to age, comorbidities, and sociodemographic factors [77]. One of the implications is that vaccinating priority populations [78] could not be addressed. We also assumed that vaccinated and recovered individuals develop immunity and are not susceptible to re-infection, which may not be the case [51, 79]. We want to emphasize that this scenario-based Tool does not forecast a future but projects a range of outcomes based on the observed data and model assumptions. These projections are best considered as helpful guides, not definitive outcomes.

Conclusions

Our interactive Tool can help local governments and hospital managers plan their response to the evolving pandemic. The Tool also creates educational value for the healthcare community and can be an important addition to planners' arsenal of models. Our Tool continues to evolve to reflect our changing understanding of SARS-CoV-2 transmission and its impact on hospital resources, and answer critical questions posed by health system planners.

The main difference between this Tool and other existing tools is its ease of use, ability to build scenarios, and ability to provide immediate outcomes that are ready to share with executive decision-makers to help them understand the evolution of the disease and make appropriate decisions.

The Tool is readily adaptable to future emerging infectious diseases and can therefore be an important addition to planners' arsenal of models for the future.

The COVID-19 Health System Capacity Planning Tool is currently available by request from CIHI (help@cihi.ca).

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Competing interests

None to be declared.

Contributors

The model conceptualization and technical development of the Epidemiological and Capacity modules were led by Olga Krylova, and the HCW/PPE module development was led by Omar Kazmi. Hui Wang led the Microsoft Excel implementation of the tool. Omar Kazmi performed the Python verification of the model. Kelvin Lam led the estimation of the healthcare usage parameters and client support. Olga Krylova and Chloe Logar-Henderson performed the formal analysis of the Ontario data and drafting of the manuscript. Overall, the project was led by Katerina Gapanenko. All of the authors revised the manuscript for important intellectual content, gave final approval of the

version to be published, and agreed to be accountable for all aspects of the work.

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Data sharing

All data used for parameterization of this model is in the public domain and can be accessed through references cited in the manuscript and technical appendix. The COVID-19 Health System Capacity Planning Tool is currently available by request from CIHI (help@cihi.ca).

Ethics statement

Our research did not require ethical approval as our research relied exclusively on publicly available and accessible data, and there is no reasonable expectation of privacy.

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A1. Model description

Our Tool consists of three interconnected modules: the Epidemiological (Epi) module, Capacity module and HCW/PPE (healthcare worker/personal protective equipment) module (Figure A.1.1). The Epi module simulates the potential spread of COVID-19 cases in the community and outputs the projected daily number of cases. This information is used in the Capacity module to estimate hospital resources including ward beds, ICU beds, and ventilators. Current hospitalization estimates are then used in the HCW/PPE module to project the number of healthcare workers and PPE required to treat hospitalized patients.

Epidemiological module

In the Epidemiological module, we used a modified version of the Susceptible-Exposed-Infected-Removed-type deterministic compartmental model with vaccination to simulate the spread of COVID-19 in a previously unexposed population. At the beginning of the simulation, all individuals are disease-free and *Susceptible (S)* to infection with SARS-CoV-2. As infectious individuals are introduced into the population, contact between susceptible and infectious individuals leads to a susceptible individual becoming *Exposed (E)* to the virus, but not yet infectious. After an average latent period ($1/\delta$), exposed individuals progress to an *Infectious* state with a proportion (P_S) of individuals moving to the *Symptomatic* (I_S) classes and a proportion ($1 - P_S$) moving to the *Asymptomatic* (I_A) class. The *Symptomatic* class is comprised of *Mild* symptomatic (I_{SM}) and *Severe* symptomatic (I_{SS}) individuals. Each infectious individual causes, on average, $R_{eff}(t)$ secondary infections while they are infectious. Infectious individuals who are *Asymptomatic* will progress to the *Recovered* (R_A) class. We assume that individuals with mild symptoms will enter a *Self-isolation* (SI_{SM}) stage before moving to the *Recovered* (R_{SM}) class. Individuals with severe symptoms will progress to the Capacity Module after a *Self-isolation* (SI_{SS}) stage after ($1/\eta_H$) days, with the mean period from symptom onset to hospitalization being 5 days. The model can also simulate deaths that occur in self-isolation (D_{SS}) before an individual is hospitalized or if hospital resources are not available. The model assumes that individuals are immune and not susceptible to re-infection once they recover.

We created a *Reported* (R) compartment to capture the 10- to 15-day "reporting delay" (d_S) between individuals being exposed to the virus and being reported as a case. It is also assumed that not all cases are reported as a high percentage are asymptomatic [1] and therefore may not be tested. At the beginning of the epidemic, it was reasonable to assume that only symptomatic cases were reported. When general population testing is introduced, a proportion of asymptomatic cases could potentially be captured in official testing statistics as well [2]. We therefore included the proportion of asymptomatic, mildly symptomatic, and severely symptomatic cases being reported, in the formula for reported cases (Table A2.1). Users can customize the delay and reporting percentages to reflect local testing policies.

We also created a *Vaccination (V)* compartment to capture the impact of vaccination rollouts that are underway. Vaccination is implemented as a step function where the daily vaccination rate (ν), vaccine efficacy (ν_E), and the delay for the vaccine (x) to be effective can be modified for different time periods (Table A2.1). This population is removed from the *Susceptible* class and can no longer add to community transmission. A relatively small proportion of vaccines will be given to individuals who may have been exposed through natural exposure (e.g., exposed individuals, individuals who are currently infectious, individuals who are recovered and have antibodies, etc.) and therefore develop natural immunity. These vaccinated individuals are not counted in the *Vaccinated* class.

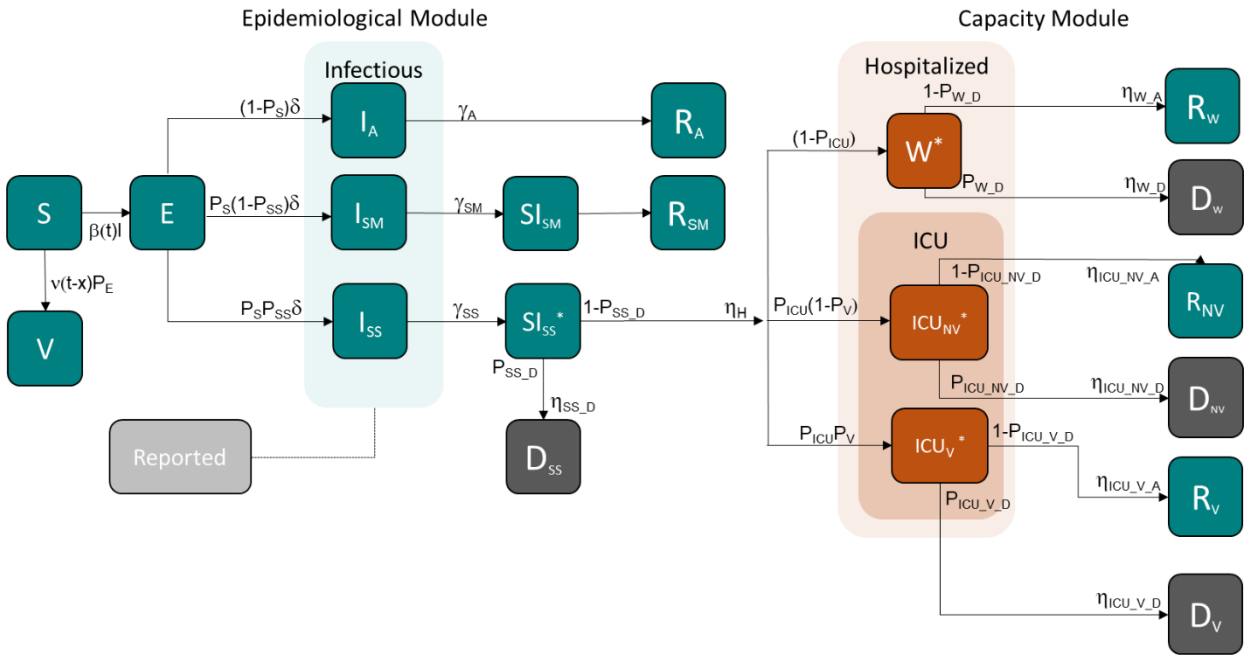
The transmission of infectious diseases within the community is associated with the reproductive power of the disease, R_0 or R_{eff} [3]. The basic reproduction number, R_0, is the average number of secondary cases produced by a single infection in a completely susceptible population, while the effective reproduction number, R_{eff}, is the actual transmission rate given public interventions and the changing proportion of susceptible individuals as the epidemic progresses [4]. In our model, similar to other SEIR-type models, the reproduction number, R_{eff} is expressed as a function of the mean transmission rate and the mean duration of infectiousness. We use a time-dependent piece-wise function for the $R_{eff}(t)$, which allows the implicit simulation of responses to publicly health policies.

Capacity module

The Capacity module estimates the hospital resources required to treat Covid-19 patients. The model is an extension of the SEIR-type model of the Epi module with three compartments representing the hospital environment (H): *Ward (W)* accounts for non-critical care inpatient beds; *ICU* represents critical care beds without ventilation; and *Ventilator (V)* signifies ICU beds with invasive mechanical ventilation. A proportion of people ($1 - P_{ICU}$) will require non-critical care (W) while a proportion (P_{ICU}) will require critical care (*Intensive Care Unit*, *ICU*). The *ICU* compartment is broken down into the proportion of patients (P_V) requiring mechanical ventilator (ICU_V) and the proportion ($1 - P_V$) who do not require mechanical ventilation (ICU_{NV}).

After hospitalization, patients could either move to the *Recovered/Discharged* or *Died* classes (Figure A1.1). Demand for hospital resources is calculated based on the proportion of patients that will use a particular resource and the length of time for which the resource will be used. Deaths in hospital can occur in any hospital setting, and the probability of death and the time until death (i.e., length of stay (LOS) for fatal patients) is specific to each compartment (Figure A1.1). A proportion of patients ($1-P_{W\_D}$) in *Ward* will move to the *Recovered/Discharged* (R_W) class after the $1/\eta_{W\_A}$ days and a proportion (P_{W_D}) will move to the *Died* (D_W) class after $1/\eta_{W\_D}$ days. Similarly, a proportion of patients in *ICU* who require ventilators ($1 - P_{ICU\_V\_D}$) will move to the *Recovered/Discharged* (R_V) class after $1/\eta_{ICU\_V\_A}$ days and a proportion ($P_{ICU\_V\_D}$) will move to the *Died* (D_V) class after $1/\eta_{ICU\_V\_D}$ days. A proportion of patients in ICU and not on ventilators (P_{ICU_NV}) will move to the *Recovered/Discharged* (R_{NV}) class after $1/\eta_{ICU\_NV\_A}$ days and a proportion ($1-P_{ICU\_NV}$) will move to the *Died* (D_{NV})

Figure A1.1: Detailed model diagram



The Diagram shows the model compartments and transitions among them.
Note: (*) denotes the compartments that are split further into two compartments (Survivals and Fatalities) but not shown in the diagram for simplicity.

class after $1/\eta_{ICU\_NV\_D}$ days. Hospital resource capacity (i.e., ward beds, ICU beds and ventilators) is included as an input to the model to estimate the potential date when resources may be depleted and to quantify the gap between bed capacity and demand.

HCW/PPE module

The HCW/PPE module estimates the number of health care workers and PPE required to care for COVID-19 patients in inpatient acute-care settings. These include nurses, physicians, respiratory therapists, cleaners, and porters as well as visitors to COVID-19 inpatients with the expectation that PPE would be provided to visitors by the healthcare facility. PPE classes include pairs of disposable gloves, eye protection (i.e., goggles or a face shield), surgical masks, N95 masks or respirators, and surgical gowns, as well as a custom slot for user-defined PPE. These numbers represent the staff and PPE that would be required to care for the COVID-19 cases only and do not consider the current staffing capacity and requirements for other patients.

As per the *WHO COVID-ESFT v2.0* [5], contact frequency for healthcare workers can be set to daily, as in the case of nurses and physicians who encounter each patient once per day, or per patient stay, as in the case of respiratory therapists who may only be required for intubating and extubating the patient. Default parameter values are presented in Tables A2.4 and A2.5.

A2. Model states and parameters

Table A2.1: Model compartments

Compartment	Definition
Population, N	Population of the province, health region, or catchment area of interest
Susceptible, S	Individuals who never contracted the virus
Vaccinated, V	Individuals who have been vaccinated
Exposed, E	Individuals who contracted the virus but haven't yet spread infection
Infectious, I	Individuals who contracted the virus and currently are infectious and spreading the virus
Infectious asymptomatic, I_A	Individuals who could spread the infection but do not exhibit symptoms while infected
Infectious symptomatic mild, I_{SM}	Individuals who could spread the infection and will develop mild symptoms
Infectious symptomatic severe, I_{SS}	Individuals who could spread the infection and will develop severe symptoms
Self-isolated, SI_{SM}	Individuals with mild symptoms who are self-isolating and not spreading the infection
Self-isolated, SI_{SS}	Individuals with severe symptoms who are self-isolating and not spreading the infection
Died in Self Isolation, D_{SS}	Individuals who die in self isolation
Hospitalized, H	Hospitalized individuals
In Ward, W	Hospitalized individuals, not in ICU
Discharged from Ward, R_W	Discharged from Ward
Died in Ward, D_W	Died in Ward
In ICU, ICU	Hospitalized, in ICU
In ICU not requiring ventilation, ICU_{NV}	Hospitalized, in ICU without mechanical ventilation
Discharged from ICU, R_{ICU_NV}	Discharged from ICU without ventilation
Died in ICU, D_{ICU_NV}	Died in ICU without ventilation
In ICU requiring ventilation, ICU_V	Hospitalized, in ICU with mechanical ventilation
Discharged from ICU after ventilation, R_{ICU_V}	Discharged from ICU after being on mechanical ventilation
Died in Ward, D_{ICU_NV}	Died in ICU after being on mechanical ventilation

Table A2.2: Model parameters

Parameter	Description and notes	Value*	References
EPIDEMIOLOGICAL			
Reproductive number, R_0 or $R_{eff}(t)$	The basic reproductive number, R_0, is the average number of secondary cases produced by a single infection in a completely susceptible population. The effective reproductive number, $R_{eff}(t)$, is the actual rate of transmission given public interventions and the changing proportion of susceptible individuals as the epidemic progresses.	Time-dependent Historical values are estimated based on the observed data. Projected values are specified by the user.	
$\beta(t)$	Transmission coefficient	Time-dependent and calculated based on $R_{eff}(t)$	
P_A	Percentage of cases that are asymptomatic	33%	Oran et al. [1]
P_S	Percentage of cases that are symptomatic, $1-P_A$	67%	Calculated
P_{SS}	Percentage of severe symptomatic cases who require hospitalization	See paper Table 2	See paper Table 2
$1/\delta$	Latent period (based on 5.1 days incubation period, i.e. from the point of infection to symptoms onset and a 1-day pre-symptomatic infectious period) $5.1-1=4.1$	4.1 days	Calculated based on Lauer et al. [6], He et al. [7]
	Incubation period - The period from the time the individual is exposed to the virus to the onset of symptoms.	5.1 days	Lauer et al. [6]
	Pre-symptomatic infectivity period	1 day	He et al. [7]
$1/\gamma_A$	Time between onset of infectiousness and recovery for someone who is asymptomatic	6 days	Hu et al. [8]
$1/\gamma_{SM}$	Time between the onset of infectiousness and self-isolation for someone who develops mild symptoms We assumed that an infected individual will self-isolate 3 days after developing symptoms	4 days	Calculated Lauer et al. [6]
$1/\gamma_{SS}$	Time between onset of infectiousness and self-isolation for someone who develops severe symptoms	4 days	Li et al. [9]
	Time from symptom onset to hospitalization	5 days	Dai et al. [10]
$1/\eta_H$	Time in self-isolation before hospitalization	2 days	Calculated
P_{SS_D}	Percentage of deaths in self-isolation (severe cases that are never hospitalized) Assumption for this version as there are no reliable data. It can be adjusted and calibrated in future versions.	0%	Assumption
$1/\eta_{\_SS\_D}$	Time to death in self-isolation (never hospitalized) (severe cases) Assumption for this version as there are no reliable data. It can be adjusted and calibrated in future versions.	N/A	Assumption
x	Vaccination effect delay - time from vaccination to full immunity	12 days	Polack et al. [11]
v	Daily vaccination rate	See paper Table 3	Government of Ontario [12]
v_E	Vaccine efficacy	95%	Government of Ontario [13]

(Continued)

Table A2.2: Continued

Parameter	Description and notes	Value*	References
HEALTHCARE USAGE			
P_H	Percentage of symptomatic cases requiring hospital admission	See paper Table 2	See paper Table 2
P_{ICU}	Percentage of cases admitted to ICU among those hospitalized	See paper Table 2	CIHI [14]
P_V	Percentage requiring mechanical ventilation among those in ICU	See paper Table 2	CIHI [14]
P_{W_D}	Percentage of deaths among cases in ward	See paper Table 2	CIHI [14]
P_{ICU_D}	Percentage of deaths among cases in ICU	See paper Table 2	CIHI [14]
$P_{ICU\_V\_D}$	Percentage of deaths among cases requiring mechanical ventilation	See paper Table 2	CIHI [14]
$1 - P_{ICU\_V\_D}$	Percentage of survivors in cases requiring mechanical ventilation	See paper Table 2	CIHI [14]
$1/\eta_{W\_A}$	Average length of stay in ward bed for survivors	See paper Table 2	CIHI [14]
$1/\eta_{W\_D}$	Average length of stay in ward bed for fatal cases	See paper Table 2	CIHI [14]
$1/\eta_{rmICU\_NV\_A}$	Average length of stay in ICU and not on ventilator for survivors	See paper Table 2	CIHI [14]
$1/\eta_{ICU\_NV\_D}$	Average length of stay in ICU and not on ventilator for fatal cases	See paper Table 2	CIHI [14]
$1/\eta_{ICU\_V\_A}$	Average length of stay on ventilator for survivors	See paper Table 2	CIHI [14]
$1/\eta_{ICU\_V\_D}$	Average length of stay on ventilator for fatal cases	See paper Table 2	CIHI [14]
REPORTING			
$P_{A\_Reported}$	Proportion of asymptomatic cases that get reported	0	Assumption
$P_{SM\_Reported}$	Proportion of mildly symptomatic cases that get reported	1	Assumption
$P_{SS\_Reported}$	Proportion of severely symptomatic cases that get reported	1	Assumption
d_S	Reporting delay - Time from initial infection to being reported for symptomatic cases	13 days	Ping, Y [15]
d_A	Reporting delay – Time from initial infection to being reported for asymptomatic cases We assume that asymptomatic cases are not reported	0 days	Assumption

*Based on the literature or available data

Table A2.3: Model equations

Model compartments	Difference equations
EPIDEMIOLOGICAL MODULE	
Susceptible (S)	$S(t) = S(t-1) - \beta(t) * S(t-1) * \frac{I(t-1)}{N(t)} - V(t-1)$
Vaccinated (V)	$V(t) = \nu(t-x) * \nu_E(t-x) * \frac{S(t-x)}{N_{vaccine\ eligible}(t-x)} + V(t-1)$
Exposed (E)	$E(t) = E(t-1) + \beta(t) * S(t-1) * \frac{I(t-1)}{N(t)} - \delta * E(t-1)$
Infectious (I)	$I(t) = I_A(t) + I_{SM}(t) + I_{SS}(t)$
– Asymptomatic (I_A)	$I_A(t) = I_A(t-1) + \delta * (1-P_S) * E(t-1) - \gamma_A * I_A(t-1)$
– Symptomatic Mild (I_{SM})	$I_{SM}(t) = I_{SM}(t-1) + \delta * P_S * (1 - P_{SS} * E(t-1) - \gamma_{SM} * I_{SM}(t-1)$
– Symptomatic Severe (I_{SS})	$I_{SS}(t) = I_{SS}(t-1) + \delta * P_S * P_{SS} * E(t-1) - -\gamma_{SS} * I_{SS}(t-1)$
Self-isolation Symptomatic Severe (SI_{SS})	$SI_{SS}(t) = SI_{SS_{Survival}}(t-1) + SI_{SS_{Fatality}}(t-1)$
	$SI_{SS_{Survival}}(t) = SI_{SS_{Survival}}(t-1) + (1-P_{SS\_D}) * \gamma_{SS} * I_{SS}(t-1) - \eta_H * SI_{SS_{Survival}}(t-1)$
	$SI_{SS_{Fatality}}(t) = SI_{SS_{Fatality}}(t-1) + P_{SS_D} * \gamma_{SS} * I_{SS}(t-1) - \eta_{SS\_D} * SI_{SS_{Fatality}}(t-1)$
Deaths in self-isolation (D_{SS})	$D_{SS}(t) = D_{SS}(t-1) + \eta_{SS\_D} * SI_{SS_{Fatality}}(t-1)$
Reported	$Reported(t) = P_{A_{Reported}} * \delta * (1-P_S) * E(t-d_A) + P_{SM_{Reported}} * \delta * P_S * (1-P_{SS}) * E(t-d_S) + P_{SS_{Reported}} * \delta * P_S * P_{SS} * E(t-d_S)$
Transmission coefficient, $\beta(t)$	$\beta(t) = \frac{R_{\text{eff}}(t)}{\frac{1-P_S}{\gamma_A} + P_S * \frac{1-P_{SS}}{\gamma_{SM}} + P_S * \frac{P_{SS}}{\gamma_{SS}}}$
CAPACITY MODULE	
Hospitalized (H)	$H(t) = W(t) + ICU(t)$
Ward (W)	$W(t) = W_{Survival}(t-1) + W_{Fatality}(t-1)$
	$W_{Survival}(t) = W_{Survival}(t-1) + \eta_H * (1-P_{ICU}) * (1-P_{W\_D}) * SI_{SS_{Survival}}(t-1) - \eta_{W\_A} * W_{Survival}(t-1)$
	$W_{Fatality}(t) = W_{Fatality}(t-1) + \eta_H * (1-P_{ICU}) * P_{W\_D} * SI_{SS_{Survival}}(t-1) - \eta_{W\_D} * W_{Fatality}(t-1)$
Intensive Care Unit (ICU)	$ICU(t) = ICU_{NV}(t) + ICU_V(t)$
ICU No Ventilator (ICU_{NV})	$ICU_{NV} = ICU_{NV_{Survival}}(t-1) + ICU_{NV_{Fatality}}(t-1)$
	$ICU_{NV_{Survival}}(t) = ICU_{NV_{Survival}}(t-1) + \eta_H * P_{ICU} * (1-P_V) * (1-P_{ICU\_NV\_D}) * SI_{SS_{Survival}}(t-1) - \eta_{ICU\_NV\_A} * ICU_{NV_{Survival}}(t-1)$
	$ICU_{NV_{Fatality}}(t) = ICU_{NV_{Fatality}}(t-1) + \eta_H * P_{ICU} * (1-P_V) * P_{ICU\_NV\_D} * SI_{SS_{Survival}}(t-1) - \eta_{ICU\_NV\_D} * ICU_{NV_{Fatality}}(t-1)$
ICU Ventilator (ICU_V)	$ICU_V = ICU_{V_{Survival}}(t-1) + ICU_{V_{Fatality}}(t-1)$
	$ICU_{V_{Survival}}(t) = ICU_{V_{Survival}}(t-1) + \eta_H * P_{ICU} * P_V * (1-P_{ICU\_V\_D}) * SI_{SS_{Survival}}(t-1) - \eta_{ICU\_V\_A} * ICU_{V_{Survival}}(t-1)$
	$ICU_{V_{Fatality}}(t) = ICU_{V_{Fatality}}(t-1) + \eta_H * P_{ICU} * P_V * P_{ICU\_V\_D} * SI_{SS_{Survival}}(t-1) - \eta_{ICU\_V\_D} * ICU_{V_{Fatality}}(t-1)$

(Continued.)

Table A2.3: Continued

Model compartments	Difference equations
Died in a hospital (D_H)	$D_H(t) = D_H(t-1) + \eta_{W\_D} * W_{Fatality}(t) + \eta_{ICU\_NV\_D} * ICU_{NV_{Fatality}}(t-1) + \eta_{ICU\_V\_D} * ICU_{V_{Fatality}}(t-1)$
Discharged from hospital (R_H)	$R_H(t) = R_H(t-1) + \eta_{W\_A} * W_{Survival}(t) + \eta_{ICU\_NV\_A} * ICU_{NV_{Survival}}(t-1) + \eta_{ICU\_V\_A} * ICU_{V_{Survival}}(t-1)$

Table A2.4: Estimating the percentage of hospitalized COVID-19 cases in Ontario, Canada

Time period	Period end date	Cumulative cases to end of period	Bi-monthly cumulative cases	Cumulative hospitalizations to end of period	Bi-monthly cumulative hospitalizations	Percent hospitalized, %
Jan–Mar 2020	31-Mar	2,392	2,392	270	270	11.3
Apr–May 2020	31-May	28,263	25,871	3,507	3,237	12.5
June–July 2020	31-Jul	39,333	11,070	4,672	1,165	10.5
Aug–Sept 2020	30-Sep	52,248	12,915	5,160	488	3.8
Oct–Nov 2020	29-Nov*	116,492	64,244	7,438	2,278	3.5
Dec 2020–Jan 2021	31-Jan	270,180	153,688	13,533	6,095	4.0

Source: Public Health Ontario. COVID-19: Epidemiologic summaries from Public Health Ontario [cited 2021 Mar 4]. Available from https://covid-19.ontario.ca/covid-19-epidemiologic-summaries-public-health-ontario
*Note that there was a data reporting issue for the November 30th Public Health Ontario report

Table A2.5: Healthcare workforce default parameter values

Staff name	Staff environment	Patient contact frequency	Contacts per patient (per shift)	Hours per shift	Patients per staff member
Nurses	Ward	Daily	2	12	6
Nurses	ICU (no ventilator)	Daily	5	12	1
Nurses	ICU (ventilator)	Daily	5	12	1
Physicians	Ward	Daily	1	12	30
Physicians	ICU (no ventilator)	Daily	1	12	10
Physicians	ICU (ventilator)	Daily	1	12	10
Respiratory Therapists	ICU (ventilator)	Stay	2	12	15
Cleaners	Ward	Daily	1	12	30
Cleaners	ICU (no ventilator)	Daily	1	12	10
Cleaners	ICU (ventilator)	Daily	1	12	10
Porters	Ward	Stay	2	12	15
Porters	ICU (no ventilator)	Stay	2	12	15
Porters	ICU (ventilator)	Stay	2	12	15
Visitors	Ward	Daily	1	24	1
Visitors	ICU (no ventilator)	Daily	1	24	1
Visitors	ICU (ventilator)	Daily	1	24	1

Table A2.6: Personal protective equipment (PPE) usage default parameter values ("Number of PPE per shift" or "Contact")*

Staff name	Staff environment	Gloves (pair)	Eye protection	Surgical masks	N95 Masks	Gowns	Custom
Nurses	Ward	Contact	1	2	0	1	0
Nurses	ICU (no ventilator)	Contact	1	0	2	1	0
Nurses	ICU (ventilator)	Contact	1	0	2	1	0
Physicians	Ward	Contact	1	2	0	1	0
Physicians	ICU (no ventilator)	Contact	1	0	2	1	0
Physicians	ICU (ventilator)	Contact	1	0	2	1	0
Respiratory Therapists	ICU (ventilator)	Contact	2	0	2	2	0
Cleaners	Ward	Contact	2	2	0	2	0
Cleaners	ICU (no ventilator)	Contact	2	0	2	2	0
Cleaners	ICU (ventilator)	Contact	2	0	2	2	0
Porters	Ward	Contact	2	2	0	2	0
Porters	ICU (no ventilator)	Contact	2	0	2	2	0
Porters	ICU (ventilator)	Contact	2	0	2	2	0
Visitors	Ward	Contact	1	1	0	1	0
Visitors	ICU (no ventilator)	Contact	1	0	1	1	0
Visitors	ICU (ventilator)	Contact	1	0	1	1	0

*The values for PPE usage were obtained from the World Health Organization(4) and from interviews with clinicians in Ontario and Newfoundland

Table A2.7: Timeline of major policies in Ontario, Canada from 1st February 2020 to 1st April 2021

Description of (de)escalation measures	Date	Source
Onset of the epidemic	2/1/2020	
Schools closed	3/14/2020	[16]
State of emergency declared	3/17/2020	[16]
Non-essential businesses closed	3/25/2020	[16]
Recreational amenities closed	3/30/2020	[16]
Overall effect of escalation measures	4/9/2020	
Overall effect of escalation measures	4/19/2020	
Select businesses reopened	5/4/2020	[16]
Use of face masks recommended	5/20/2020	[16]
24 regions entered Stage 2 of reopening	6/12/2020	[16]
7 additional regions entered Stage 2 of reopening	7/19/2020	[16]
Public schools opened	9/8/2020	[16]
Targeted escalation measures for 4 regions	10/10/2020	[17]
5 regions moved into red zone	11/13/2020	[18]
2 regions enter lockdown phase	11/23/2020	[19]
2 weeks before Christmas	12/11/2020	
Elevated risk levels for 7 regions	12/14/2020	[20]
Province-wide lockdown	12/26/2020	[21]
Stay-at-home ordered and state of emergency declared	1/12/2021	[22]
3 regions to reopen	2/10/2021	[23]
Additional 27 regions to reopen	2/16/2021	[24]
Additional 3 regions to reopen	3/8/2021	[25]
Further lifting of restrictions	3/21/2021	[26]
Overall effect of lifting of restrictions	4/1/2021	

A3. Model validation

We validated the Tool results against two benchmarks. First, an internal validation was done to ensure that outputs produced by the model aligned with historical case, hospitalisation, intensive care unit (ICU) admissions, and ICU admissions with ventilation data. Second, we compared outputs from the model with case and hospitalisation estimates generated by other major models (the McMaster Pandemic model [27], the online Epidemic Calculator [28], University of Pennsylvania's CHIME PPE Calculator Excel application [29], and COVID-19 Modeling Collaborative's PPE Resource estimator [30].

A3.1 Internal validation

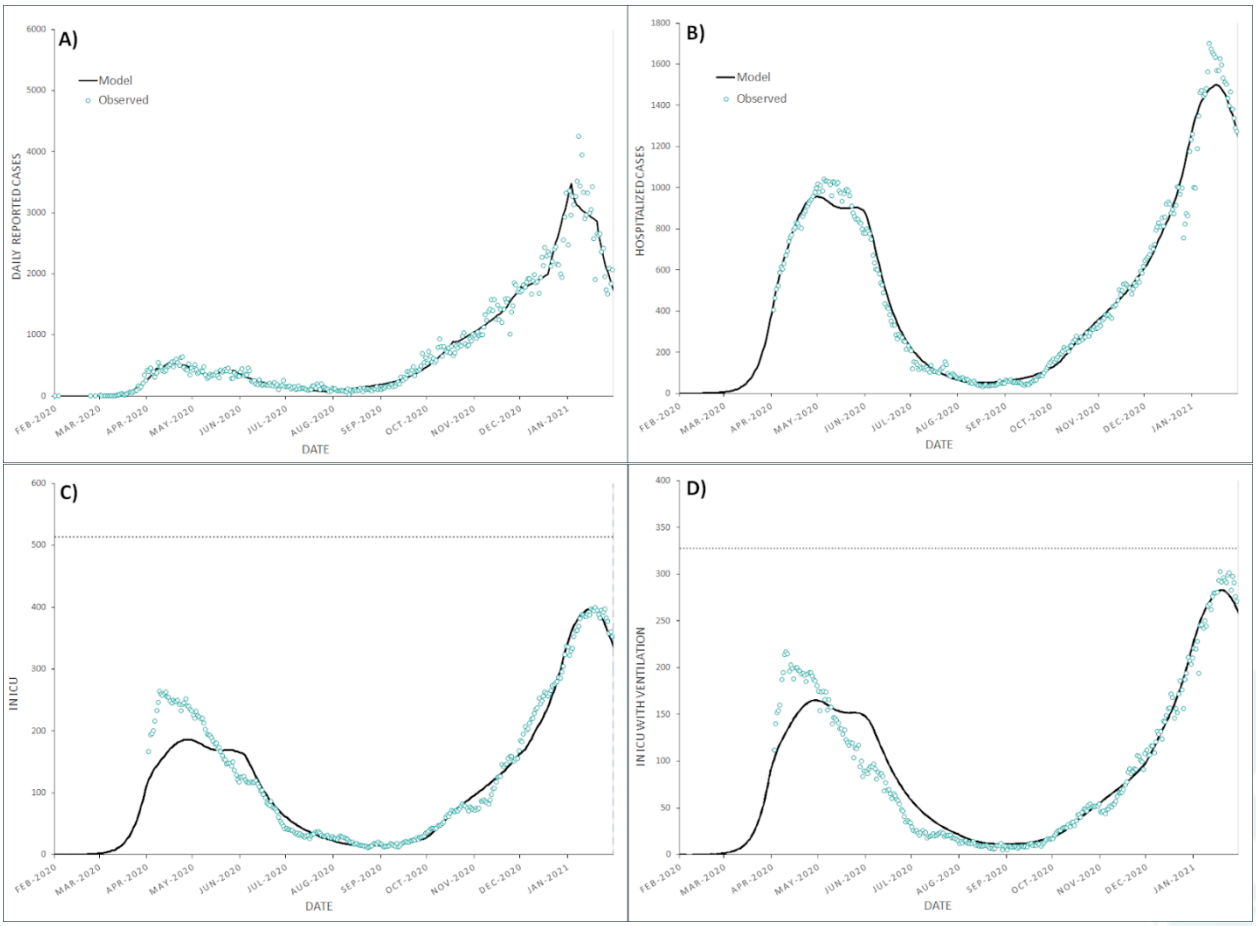
Figure A3.1 shows the graphical comparison of the outputs from the model against the historical data for Ontario. Outputs from CIHI's Tool are shown as a black line, while the teal circles represent the historical data. The four panels are A – daily cases, B – number of people in hospital per day, C – number of people in ICUs per day, and D – number of people in ICU on ventilator per day.

An analysis of the model fit with the Mean Absolute Percentage Error suggests that the model performs very well, with a MAPE between 8% and 18%, indicating a good calibration of the model. The model shows a better predictive power for daily number of cases (MAPE = 4%), daily number of people hospitalized (MAPE = 8%), and number of people in ICU (MAPE = 13%) than for daily number of people on ventilators (MAPE = 18%). The model's predictive power improves over time and the goodness of fit is higher for more recent data (i.e., the most recent 1.5-2 months) compared to the earlier phases of the epidemic (i.e., the first 1–1.5 months since the first case).

A3.2 Comparison with similar models

In the second part of our external validation process, we compared the projected number of active cases, daily number of people in need of non-critical and critical care beds, peak hospitalization demand (volume and date), peak ICU demand (volume and date), deaths, and final attack rate, with outputs of two SEIR-based mathematical models: the McMaster Pandemic model [27], and the Epidemic Calculator [28] and obtained very similar results. The HCW/PPE (Health

Figure A3.1: Comparison of the model outputs from the CIHI's capacity tool and historical data from Ontario



The model is validated against historical data on daily cases (A), number of people in hospital per day (B), number of people in ICUs per day (C), and number of people in ICU on ventilator per day (D) in Ontario for the one year since the beginning of the pandemic (1st February 1 2020 until 31st January 2021). Model fit: MAPE = 13.4% for daily cases, MAPE = 8.45% for hospitalizations, MAPE = 12.8% for ICU data, and MAPE = 18.4% for ventilators.

Table A3.3.1: Projection of the validation scenarios

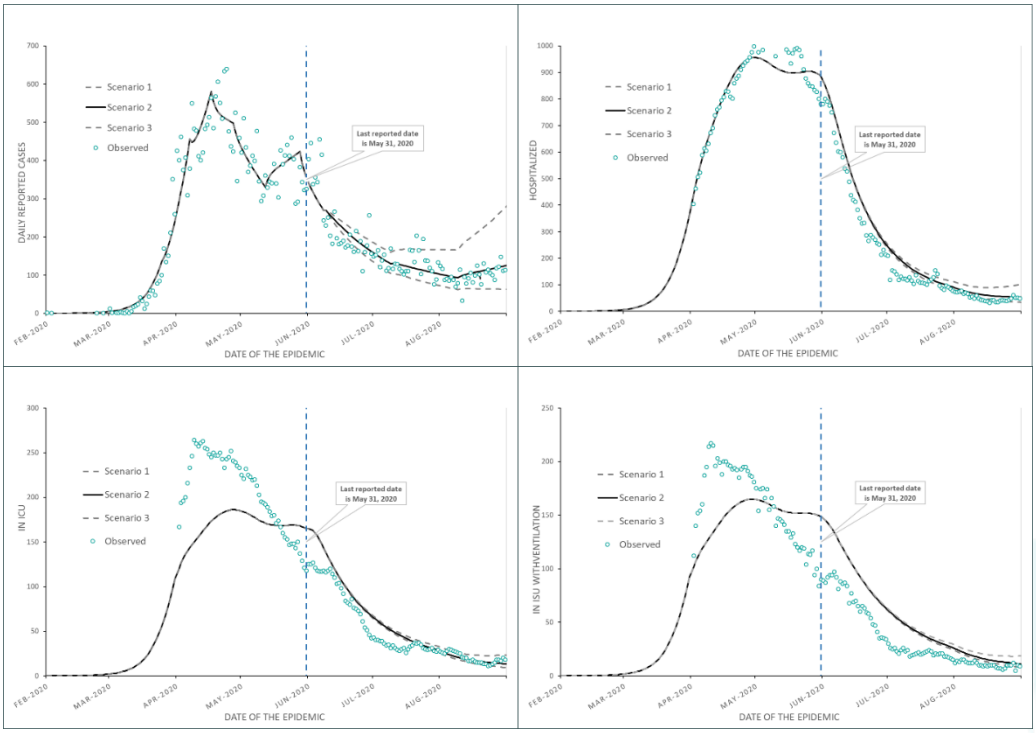
		Scenario 1	Scenario 2	Scenario 3
Potential changes in $R_{eff}(t)$				
Public health announcements	**Date**	**$R_{eff}(t)$**	**$R_{eff}(t)$**	**$R_{eff}(t)$**
Potential lifting of restrictions	1st June 2020	0.75	0.8	0.85
Potential lifting of restrictions	1st July 2020	0.85	0.9	1
Potential lifting of restrictions	1st August 2020	0.99	1.1	1.2
Potential changes in hospital usage parameters				
Percentage of cases requiring hospitalization, %	1st June 2020–31st August 2021	3	3	3
Percentage admitted to ICU among those hospitalized, %	1st June 2020–31st August 2021	23	23	23
Percentage of ICU admissions with mechanical ventilation, %	1st June 2020–31st August 2021	50	50	50
Capacity available for patients with COVID-19 [31]				
Hospital beds [31]	1st June 2020–31st August 2021	4,514	4,514	4,514
ICU beds [31]	1st June 2020–31st August 2021	514	514	514
Additional 500 "surge beds" [32]	1st June 2020–31st August 2021	1,014	1,014	1,014
ICU beds with ventilator	1st June 2020–31st August 2021	328	328	328

Note: For simplicity of implementation, we made a conservative assumption that the daily vaccination rate reflects the number of people who receive two doses of the vaccine with an efficacy of 95% [13].

Table A3.3.2: Healthcare Usage projections for validation scenarios

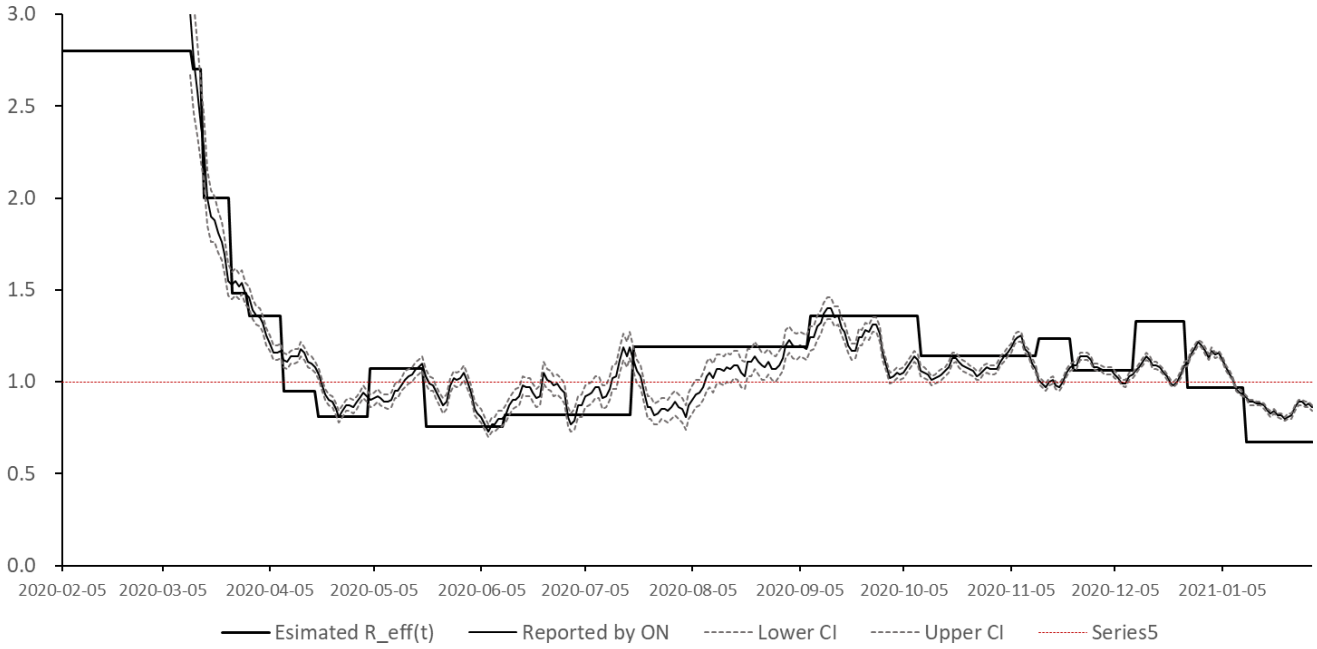
Projected values for 1st September 2021	**Observed**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Daily reported cases	114	63	125	277
Hospitalized cases	49	34	54	100
In ICU	18	9	14	23
In ICU with ventilator	9	8	11	18

Figure A3.3.1: Validation scenarios



Care Worker/Personal Protective Equipment) module was validated against the University of Pennsylvania's CHIME PPE Calculator Excel application [29], which uses similar usage and staffing parameters. Overall, the three models produced very similar outputs, with no statistical differences across the three models.

Figure A3.4: Comparison of the effective reproductive number estimated by the *COVID-19 Healthcare Capacity Planning Tool* versus those published by the Government of Ontario



The HCW/PPE (Health Care Worker/Personal Protective Equipment) module was validated against the University of Pennsylvania's CHIME PPE Calculator Excel application [29], which uses similar usage and staffing parameters. Both models produced approximately proportional results, considering some underlying differences in the models. This module was also compared to the COVID-19 Modeling Collaborative's PPE Resource estimator [30], also using comparable parameters, again with reasonably similar results considering the different underlying assumptions.

A3.3 Testing model scenarios

We also tested the model's ability to produce potential scenarios by fitting Ontario data from the first four months of the pandemic (February-May 2020) and created scenarios for the three subsequent summer months (June-August 2020). In our worst-case scenario, R_{eff} increased to 1.2 within the 3-month forecast period. In the baseline scenario, R_{eff} is increased but kept below 1.1, and in our best-case scenario, R_{eff} is kept below 1. We also significantly reduced hospitalization and ICU and ventilator use rates to account for changes in the age distribution of cases when younger adults were predominantly affected by COVID-19 with much less severe outcomes. Since our Tool is scenario-based, we verified that the observed cases for this 3-month period were within the range of our worst and best-case scenarios (as shown in Figure A3.3.1).

A3.4 Validating R_{eff} (t) estimates

We also validated our estimates for the reproduction number in Ontario from 1st February 2020 to 31st January 2021 by comparing them with the $R_{eff}(t)$ reported by Ontario. We found that our estimated $R_{eff}(t)$, which is represented by a time-dependent piece-wise function, is a close approximation to the values reported by the province of Ontario [33] (see Figure A3.4 below).

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