Optimal hybrid opening plans for York University in Fall 2021 during the COVID-19 pandemic - Is complete closure the best strategy?

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ABSTRACT

Currently, there is considerable uncertainty as to how best structure education in the coming months. It is the hope of many that, given vaccine roll-out, we will be able to fully reopen Universities for the coming fall semester, including York University. Unfortunately, it is the opinion of this work that due to the close proximity and density of the standard school environment, full reopening is not the best strategy.

To include the possibility of some in-person learning, a blended model was used to model the diffusion of an epidemic within York University using an SEAIR model and external infections. A suitable loss function was then formed to evaluate the possible reopening plans. It is found that out of a maximum of 50 opened hours per week, 7 and 30 hours are optimal for low and moderate infectious susceptibility.

1 INTRODUCTION

Since March 2020, Canadian Universities have been closed for in-person learning. Most of the remote learning techniques developed were arranged in a hurry and have not changed since their inception. As such, the desire for a return to in-person learning continues to increase as vaccines become more widely available and public impatience grows commensurate to the pandemic length.

Despite this, there is considerable uncertainty as to how the pandemic will develop into the fall. While the case rate improvements in the U.S. are encouraging, we cannot be certain that in close-proximity school-like environments we will have acceptable threshold case rates. Furthermore, case rates are still higher than before vaccine roll-out, which further complicates its perceived effectiveness. This is especially concerning since it is of mass opinion that the quality of education has decreased, [8] especially for students from less advantaged contexts. [4] As a result, it should be considered that learning and education are one of the biggest issues of the pandemic for Canada.

To help reconcile the difficulties of the pandemic and human needs, it is important to develop sustainable opening strategies. Specifically, we wish to maximize the number of in-person learning days while minimizing additional infectious transmissions at the level of York University. Some inherent difficulties of this process are that it is difficult to estimate the transmission rate within schools since most dynamics are estimated using public case rates. Furthermore, school individuals can potentially be exposed to external infections, asymptomatic individuals are difficult to detect within said age group (majority of age 18-22), and policy-making often adds extraneous variables.

In this project, a reasonable model is provided whose set-up and related parameter estimation incorporates locally-relevant transmission dynamics to a single school (York University). An optimization of the potential outcomes is then outlined and studied. Blended solutions come out as feasible and maximally efficient in containing the spread of the virus. Combined with some detection of asymptomatic cases and an increasing vaccine density, the optimal opening scenario could offer a sustainable case rate for the coming months. The solutions provided are also flexible and could be adapted to other school scenarios.

2 METHODOLOGY

2.1 Epidemic Model

The diffusion of the COVID-19 virus amongst staff and students was modelled with a suitable system of ordinary differential equations. Specifically, we consider the SEAIR model, an extension of the SIR model. This is a good model for considering transmission within a school since it includes an external source of infection, accounts for asymptomatic infections, and includes a control variable to be outlined below. [6]

The population (N) is segmented as follows: susceptible (S), exposed (pre-symptomatics) (E), asymptomatic (A; infected and infectious), infected (I), and removed/recovered (R). The model is non-dimensionalized so that $S + E + A + I + R = 1$ for any control variable.

In this model, the assumption is made that susceptible individuals may become exposed (E) after transmission. During this period of latency, individuals are infectious and have contracted the virus but do not yet show symptoms. The infection is caused by traditional contact with other infected individuals at a rate of $\beta c(t)$, or by contact occurring outside the school at a rate of α (which will be explained in the parameter selection section.) To account for the difficulty in tracking asymptomatic individuals, a screening procedure with effectiveness η (false screening rate) is used to reduce these contacts.

Exposed (E) individuals either can either become infected and asymptomatic (A), or simply infected (I) at rates γ and δ respectively. In sum, COVID-19 is carried only by E,A,I individuals, and A,I-individuals recover at rate ρ. Mortality is ignored since the majority of the population at York University consists of young students unlikely to become seriously ill.

As stated, the advantage of the SEAIR model is the inclusion of an external source of infection and a control on the number of working hours per day.

In all, the system of ODEs for York University may be modelled as follows:

$$\frac{dS}{dt} = -\alpha(1-c(t))S - \beta Sc(t)(E+\eta A) \quad (1)$$

$$\frac{dE}{dt} = \beta Sc(t)(E+\eta A) + \alpha(1-c(t))S - (\gamma+\delta)E \quad (2)$$

$$\frac{dA}{dt} = \gamma E - \rho A \quad (3)$$

$$\frac{dI}{dt} = \delta E - \rho I \quad (4)$$

$$\frac{dR}{dt} = \rho(A+I) \quad (5)$$

Time is modelled per hour and maximum time is considered out of the usual 15 week semester, hence, $t \in [0, 2520]$. Randomness is included in the initial infected population at a rate of $0.01 * r$ where $r \in [0, 1]$. Therefore, $S(0) \approx 1$ and $S(0) + E(0) = 1$.

The control function $c_n(t)$ is a simple binary function that zeros when school is remote and equals one when not (open). It considers school starting at 8 am and ending at $8 + n_{max}/5$ where $n_{max} \in [0, 50]$ (which is a variable to be optimized.) Thus full re-opening is $n_{max} = 50$ (see Figure 1.) and fully-remote learning is $n_{max} = 0$. $c_n(t)$ also zeros on weekends and we include for 1 reading week.

The model will be solved using standard Runge-Kutta methods (ODE45 in MATLAB).

2.2 Analysis

Theorem 1: For each of (1)-(5), $S+E+A+I+R$ (the total population) is closed. [6]

Proof: Let $\phi : t \longrightarrow S(t) + ... + R(t)$. Then $\phi(0) = 1$ and $\frac{d\phi}{dt} = 0, \forall t$. By the uniqueness of linear DE solutions, $\phi \equiv 1$. □

Theorem 2: $0 \leq S, E, A, I, R \leq 1$. [6]

Proof: Since $S + E + A + I + R = 1$, the right side follows. For the left side, we know $R(0) \geq 0, R'(t) > 0$, so $R(t) \geq 0, \forall t$. S,E,A,I need to take a value of 0 before becoming negative, so let us consider some cases.

$I(t) = 0, A(t) = 0 \implies I'(t) > 0, A'(t) > 0$ *exor* $E(t) = 0$. This implies $E'(t) > 0$ unless S(t)=0. The latter implies all $\frac{d^n S(t)}{dt^n} = 0$ (so $S(t) \equiv 0$) or S=0, so again, by the uniqueness of linear DE solutions, it is non-negative. □

2.3 Parameter Selection

The two parts of the main analysis fall under the variation of a parameter s, which we shall consider as a catch-all called susceptibility. This parameter is meant to be a flexible adjustment to β, and considers generally infectious dynamics such as vaccine per capita, variants of concern (VOC), and proximity. In particular, we consider at most a moderate susceptibility, assuming vaccine roll-out will meaningfully reduce the spread of the COVID-19 and VOCs.

The population of York University (N) is approximately 60000. [2] Comparing this to the population of York Region (N_{YR} = 1100000), [3] we get our multiplicative ratios of $\frac{55}{3}$ (11000000/60000) and $\frac{3}{55}$ for α and β respectively.

In addition, all parameters need to be scaled to an hourly rate so the transmission dynamics used are multiplied by a factor of $\frac{1}{24}$. Estimates for the daily infection rate β are around 0.4, but we adopt a higher value of 0.9 considering the density of school interaction. Average contacts within the school are estimated to be ≈ 100, and average contacts outside of school are taken as 9.445. [9]

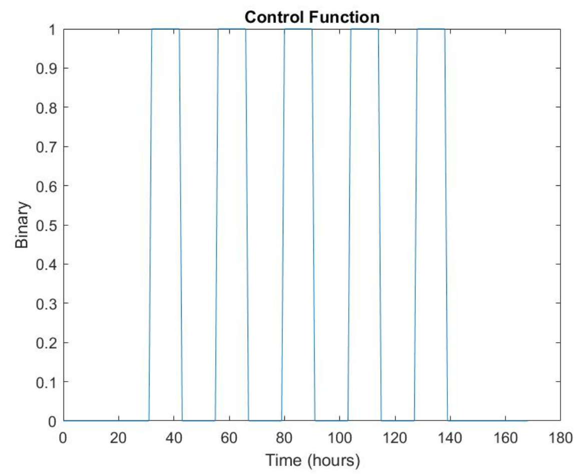

Figure 1: An example of one of the control functions with $t_{max} = 50$

As for the control function, the maximum hours allowed per week is used to scale α and β by dividing by $24 - \frac{n_{max}}{5}$ and $\frac{n_{max}}{5}$ respectively.

The standard designated recovery time for infected individuals in Ontario is two weeks, [1] so per hour, $\rho = 1/(14 * 24)$. We take $\eta \approx 0.1$, [6] as mentioned above to be a measure for quick screening.

The duration of the latency period before infected individuals potentially develop symptoms is around 5 days, [5] therefore, we need $\delta + \gamma = 0.2$. It is also known that in 20 years olds, the ratio of asymptomatic to infected individuals is approximately 3:2, [7] which gives us our values of $\gamma \approx 0.12/24, \delta \approx 0.08/24$.

Table 1: Parameter Summary

Parameter	Value
α	$s * (55/3) * 9.445/(24 - n_{max}/5)$
β	$s * (3/55) * 100/(n_{max}/5)$
η	0.1
s_i	$\vec{v}(i)$
γ	$0.12/24$
δ	$0.08/24$
ρ	$1/(24 * 14)$

The initial condition E(0) was formulated as $0.01rN$ as mentioned above.

2.4 Permutation Simplification

Given that students do not typically remain on campus a standard $n_{max}/5$ hours per day, it follows that the disbursement of their allotted hours forms a fairly complex combinatorial optimization problem. For example, it is possible to consider using 10 hours for Monday and Tuesday at ratio 3:7 instead of 5:5.

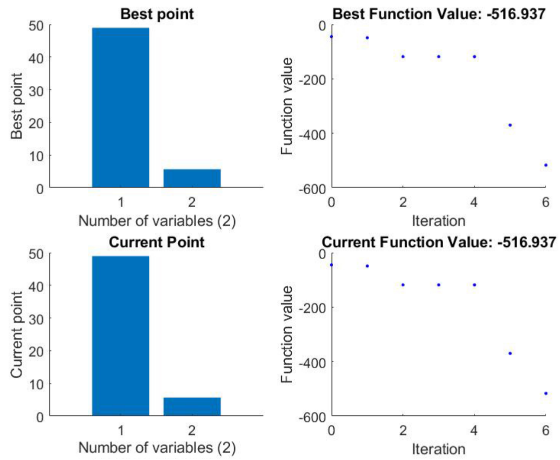

Figure 2: An example of Simulated Annealing on our ODEs with varying n and τ

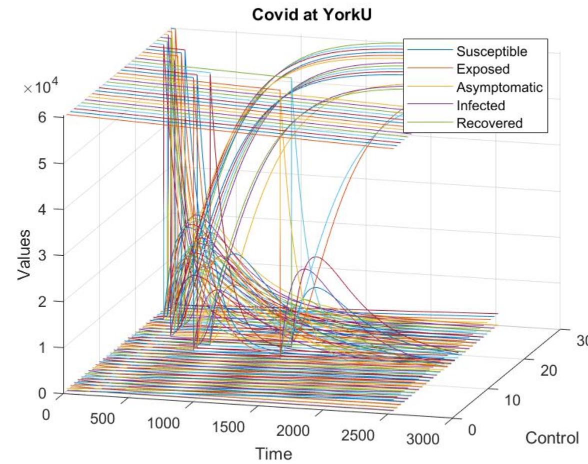

Figure 3: Amalgamated plot of the ODE solutions to varying $c_n(t)$. Note that there is no outbreak for a sufficiently strict control procedure.

All things considered, it is assumed that given all students and their differing schedules, the average amount of hours spent on campus would equal the even allotment of hours per day (from n_{max}). In the future, a data-based investigation may be performed to assess this hypothesis.

2.5 Loss Function

The main point of our analysis was to include a function that characterizes our aim of maximizing the number of in-class days while minimizing the additional infections caused by this approach. We use a standard method from optimal control theory with a relative weight τ between the two objectives.

Let $S_n(t)$ be our solution to ODE (1) at $n \in [0, 50]$. Then $S_0(0) - S_0(T)$ is the number of individuals who become infected outside of York University, and $S_n(0) - S_n(T)$ is the number of individuals who become infected at York University with plan $c_n(t)$ as well as outside transmissions. Also, let

$$N(c) = 750 - 15 * 5 * \int_0^T c_n(t)dt$$

(15weeks*5days*10hours=750), be the number of remote teaching hours. The loss function we desire is a combination of the above factors:

$$\mathcal{L} = [(S_c(0) - S_c(T)) - (S_0(0) - S_0(T))] + N(c)/\tau \tag{6}$$

2.6 Optimization by Simulated Annealing

All things considered, our objective, then, is:

$$min_c \mathcal{L} \tag{7}$$

This will be approached with Simulated Annealing for a function of n and τ. If solutions with identical loss are found, we will select the value with a larger n. See Figure 2.

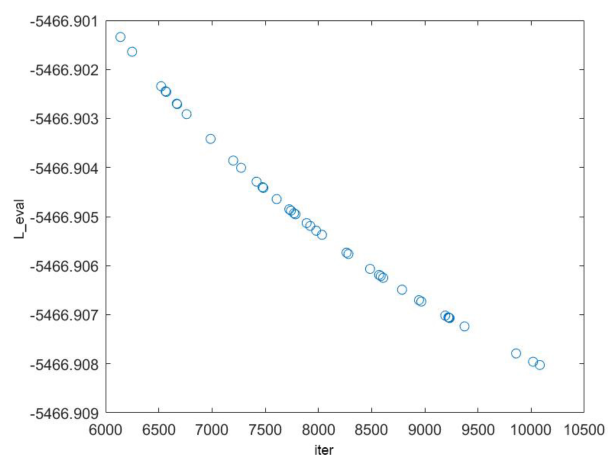

Figure 4: Late-stage $\mathcal{L}$ for a fixed $c_n(t)$. Note the smooth curvature.

3 RESULTS

For low susceptibility to the virus (lower $\vec{v}(i)$), we obtain $n \approx 7$ as the optimal hours of operation per week. For a moderate amount ($\vec{v} = 0.6$), it is found that $n \approx 30$ is the solution. Given the potential variety of $\vec{v}(i)$, a spectrum of results may be plotted to great computational expense. Minor tests suggest this to be the case. Vaccine roll-out may be interpreted as a lower index $\vec{v}(i)$.

4 DISCUSSION

4.1 Related extensions

It is clear that all things considered, parameter estimation is where most of the ambiguity in the model lies. Given in-school statistics, by comparing projected to reopened results, it is possible this results could be scaled to the university setting for a more accurate α and β.

This same approach could be used to refine the model in the future by gathering university-relevant transmission dynamics. While this will be too late for the desired predictability of the model, it is still useful to have for the investigation of long-term VOCs.

4.2 Conclusion

In all, it is found that given a reasonable ODE model with a control function, neither full-closure nor full-reopening are optimal strategies. Given a sufficiently strict control, it is possible to open York University without any outbreaks within the student body. Vaccine roll-out would, then, permit an increase in the number of hours open per day.

Indecisiveness is another area this result lends insight. Instead of debating between the binary open or closed approaches to the fall, it is clear that a spectrum of results is possible and that even a conservative choice is still more mathematically ideal than full-closure. Considering the length of the pandemic already, this is a result that may be encouraging to many.

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