



Editor:
Wasu Pathom-aree,
Chiang Mai University, Thailand

Article history:
Received: May 18, 2020;
Revised: August 14, 2020;
Accepted: September 8, 2020;
<https://doi.org/10.12982/CMUJNS.2021.016>

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Research article

Predictive Model for the Total Daily COVID-19 Cases with Herd Immunity Policy

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Abstract The spread of coronavirus disease 2019 (COVID-19) has caused a pandemic, and policies for fighting COVID-19 have been enacted by the governments of most countries. The herd immunity policy is the policy that Sweden is using to fight COVID-19. The purpose of this research is to estimate the number of total COVID-19 cases in Sweden in which herd immunity is being encouraged. A logistic model was selected as the predictive model for estimating the number of COVID-19 cases in Sweden and the other Nordic countries in which the strict lockdown policy has been instigated, and a comparative study between them was conducted and validation of the predictive models was confirmed. The findings show that the herd immunity policy is applicable and acceptable but flattening the predictive curve by applying the herd immunity policy is slightly slower than when applying the strict lockdown policy.

Keywords: Coronavirus disease 2019, Herd Immunity, Logistic Model, Least-squares Method

Citation: Sunthornwat, R., and Areepong, Y. 2021. Predictive model for the total daily COVID-19 cases with herd immunity policy. CMUJ. Nat. Sci. 20(1): e2021016

INTRODUCTION

Coronavirus 2019 is an RNA virus with a strong envelope protein and its structure resembles a crown shape that comprises three proteins: spike, nucleocapsid, and membrane. The spike protein matches a receptor on the cell surface of human lung tissue (Cui et al., 2019; Wu et al., 2020), and coronavirus 2019 is incorporated via endocytosis (Marsh and McMahon, 1999). When a person contracts coronavirus disease 2019 (COVID-19), inspiration can fail due to pneumonitis, which is the main cause of death from COVID-19. The three main methods for fighting COVID-19 consist of vaccination, herd immunity, and natural protection from mutation.

Coronavirus 2019 has been spreading in the Nordic countries in northern Europe since around the end of January 2020. Moreover, the spread of coronavirus 2019 has been wide spread throughout the world, especially in Sweden with its epicenter in Stockholm. One of the important factors for different spreading rates in the Nordic countries is each government's policy for administering and controlling the spread (Baniamin et al., 2020). While Sweden's government has adopted the herd immunity policy, the other Nordic countries (Norway, Finland, and Denmark) have applied the strict lockdown policy consisting of prohibition of international transportation (especially air transportation), social and physical distancing, working from home, avoiding assemblies of large numbers of people, washing hands with alcohol gel or soap, wearing a mask in the community, etc.

As mentioned, Sweden has adopted the herd immunity policy during the COVID-19 outbreak (Holly, 2020; Strang, 2020), which is different from the strict lockdown policy. For the herd immunity process to proceed, infected people are estimated at 60%, with 30% of them having recovered. Subsequently, as the number of people who have recovered increases, other people in the community become protected. The situation of herd immunity policy in Sweden is as follows. Swedish people regularly enjoy life but they have to be responsible for themselves and society. Schools and academic institutes are still open, as are clubs, bars, and businesses. Some rules have been enacted; for example, an assembly of more than 50 people is not allowed and social distancing is enforced among people at tables in restaurants.

The population size of Sweden is around 10 million people. New COVID-19 cases in Sweden are only slightly increasing like many countries in Europe, such as Italy, Spain, Great Britain, etc. Sweden's government does not prevent people from becoming infected with COVID-19 widely, there by encouraging herd immunity.

The focus of this study is on the herd immunity policy adopted by the government of Sweden for protecting public health and preventing the spread of COVID-19 and comparing their outcomes with the other Nordic countries that have applied the strict lockdown policy.

Obviously, knowing the number of cumulative COVID-19 cases is key for developing policies to fight the COVID-19 outbreak. Remarkably, the number of cumulative COVID-19 cases forms an S-curve. Because a logistic model does the same, it can be used to represent the cumulative COVID-19 cases. Predictive models with logistic curves have been studied by many researchers in several fields. Ji (2013) applied a logistic model for forecasting the growth of durable consumer goods in China. Eberhardt and Breiwick (2012) used logistic curves for describing the population growth of sizable numbers of birds and mammals. Anastasia et al. (2017) analyzed the epidemiological dynamics of World Health Organization data with logistic functions. Valentina (2015) analyzed and forecasted greenhouse diffusion from Albanian agriculture based on logistic curves for decision-making on maximum profit and minimum loss. Tsoularis and Wallace (2002) developed a model based on a logistic function for population dynamics and biological growth; analysis of some properties and proof of the curve fitting of logistic growth was also presented.

The purpose of this research was to study the predictive model established via logistic modeling to estimate the daily number of total COVID-19 cases in Sweden, in which the herd immunity policy for fighting COVID-19 was adopted, and compare the results with the strict lockdown (flattening the curve) policy adopted by the other

Nordic countries (Norway, Finland, and Denmark). Validation of the predictive model is demonstrated via statistical measurements. The mathematical and statistical background as the material and methods for this research are also covered herein.

MATERIALS AND METHODS

Data collection

Data on the daily COVID-19 cases in the Nordic countries (Sweden, Norway, Finland, and Denmark) was gathered as secondary data from the Worldometer (2020) website. The time period of data is from February 15, 2020, ($t = 0$) to May 11, 2020 ($t = 86$). The collected data was intact without any missing data. For the predictive model, the independent variable was time (days) and the dependent variable was the daily number of COVID-19 cases in the Nordic countries. In addition, the data analysis was carried out by using MATLAB programming (Kharab and Guenther, 2012).

The logistic model

The assumption for this research is that a logistic model can be used as the predictive model for describing the daily COVID-19 cases in the Nordic countries. Thus, the population size of daily COVID-19 cases in the Nordic countries is estimated by the logistics differential equation, which is solved as follows:

Let $p(t)$ be the population size of daily COVID-19 cases in the Nordic countries at any time $t \geq 0$. The logistic model for which the solution of the logistic differential equation was first presented by Verhulst (Verhulst, 1838) is

$$\frac{d}{dt} p(t) = gp(t) \left[1 - \frac{p(t)}{C} \right]; p(t=0) = p_0 \quad (1)$$

with the initial population size of daily COVID-19 cases $p_0 > 0$, growth parameter $g > 0$, and carrying capacity parameter C .

The solution to Equation (1) is achieved via the separable and partial fraction methods (Martha and James, 2018).

$$\int \frac{1}{p(t) \left[1 - \frac{p(t)}{C} \right]} dp(t) = \int g dt$$

$$\int \left(\frac{1}{p(t)} + \frac{1}{C - p(t)} \right) dp(t) = \int g dt$$

$$\ln \left| \frac{p(t)}{C - p(t)} \right| = gt + A \text{ where } A \text{ is arbitrary constant.}$$

Thus, the result is:

$$p(t) = \frac{C}{1 + K \exp(-gt)} \text{ where } K = \frac{C - p_0}{p_0}$$

The Least-squares Method for Estimating the Parameters

The least-squares method was applied to estimate the parameters of the prediction model for the daily number of COVID-19 cases in the Nordic countries. The main approach for the least-squares method is to fit the logistic function and the observations by estimating the appropriate parameters for the logistic function as the minimum error between the observations and the estimate values using the model. The logistic function is derived as

$$p(t) = \frac{C}{1 + K \exp(-gt)} \text{ where } K = \frac{C - p_0}{p_0}.$$

For the set of n observations at time t_i and the daily number of COVID-19 in Nordic countries $p(t_i) = p_i$,

$$\{(t_0, p_0), (t_1, p_1), (t_2, p_2), \dots, (t_n, p_n)\} = \{(t_i, p_i) | i = 0, 1, 2, 3, \dots, n\}$$

Let p_i be the actual value for the i^{th} observation, \hat{p}_i be the i^{th} estimated value from the predictive model, and e_i be the error between the actual value and estimate value. Thus,

$$e_i = p_i - \hat{p}_i \text{ for } i = 0, 1, 2, 3, \dots, n$$

To summarize the squared-error $f(C, g)$ with two independent variables C and g ,

$$\begin{aligned} f(C, g) &= \sum_{i=1}^n e_i^2 \\ &= e_1^2 + e_2^2 + e_3^2 + \dots + e_n^2 \\ &= \left[p_0 - \left(\frac{C}{1 + K \exp(-gt_0)} \right) \right]^2 + \left[p_1 - \left(\frac{C}{1 + K \exp(-gt_1)} \right) \right]^2 + \dots + \left[p_n - \left(\frac{C}{1 + K \exp(-gt_n)} \right) \right]^2 \\ &= \sum_{i=0}^n \left[p_i - \left(\frac{C}{1 + K \exp(-gt_i)} \right) \right]^2 \end{aligned}$$

To minimize the sum-of-squares error, the critical values (C^*, g^*) are calculated by applying $\frac{\partial f}{\partial C} = 0$ and $\frac{\partial f}{\partial g} = 0$, and must correspond to the minimum value of the sum-of-squares error function as follows:

Let H be a Hessian matrix of second partial derivatives.

$$H = \begin{bmatrix} f_{CC} & f_{Cg} \\ f_{gC} & f_{gg} \end{bmatrix}$$

If $\det[H(C^*, g^*)] > 0$ and $f_{CC}(C^*, g^*) > 0$ then f has a minimum at (C^*, g^*) .

Analysis of the predictive model

The analysis of the logistic model describing the daily COVID-19 cases in Nordic countries was conducted by studying the asymptotical behavior when the time approaches infinity.

$$p(t) = \lim_{t \rightarrow \infty} \left[\frac{C}{1 + K \exp(-gt)} \right] = C$$

Thus, when the time tends toward infinity, the population size of the daily COVID-19 cases will approach the carrying capacity. The maximum daily COVID-19 cases is derived from the derivative of the logistic function as follows:

Let $\frac{d}{dt} p(t)$ denote the spreading rate of COVID-19. The maximum daily COVID-19 rate occurs at the inflection point of the logistic function at which $\frac{d^2}{dt^2} p(t) = 0$.

$$\begin{aligned} p'(t) &= -C[1 + K \exp(-gt)]^{-2} [-gK \exp(-gt)] \\ &= CgK \exp(-gt)[1 + K \exp(-gt)]^{-2} \\ p''(t) &= -C[1 + K \exp(-gt)]^{-2} [Kg^2 \exp(-gt)] + 2C[1 + K \exp(-gt)]^{-3} [Kg \exp(-gt)]^{-2} \\ &\quad - C[1 + K \exp(-gt)]^{-2} [Kg^2 \exp(-gt)] + 2C[1 + K \exp(-gt)]^{-3} [Kg \exp(-gt)]^{-2} = 0 \\ 2[1 + K \exp(-gt)]^{-1} &= \frac{1}{K \exp(-gt)} \\ 1 - K \exp(-gt) &= 0 \\ t &= \frac{\ln(K)}{g} \end{aligned}$$

Therefore, the maximum daily COVID-19 rate occurs at $p(t) = \frac{C}{2}$, after which the curve slowly starts to flatten. On the other hand, the daily COVID-19 cases increase to the maximum at half the carrying capacity before the slow start.

To sum up, the time for the fastest daily spread of COVID-19 is at $t = \frac{\ln[(C - p_0) / p_0]}{g}$ after the initial outbreak ($t=0$). At the peak of the outbreak,

$p' \left(\frac{\ln[(C - p_0) / p_0]}{g} \right)$ new people become infected every day. The time at which the

spread of the disease starts to slow down is after the peak at $t = \frac{\ln[(C - p_0) / p_0]}{g}$,

and the number of daily COVID-19 cases then approaches the carrying capacity.

However, the first and the second derivatives of $p(t)$ at point t^* are originally defined and estimated as

$$\begin{aligned} \frac{d}{dt} p(t^*) &= \lim_{t \rightarrow t^*} \frac{p(t) - p(t^*)}{t - t^*} \\ &\approx \frac{C(t+1) - C(t-1)}{2\Delta t} \end{aligned}$$

$$\frac{d^2}{dt^2} p(t^*) = \frac{d}{dt} \left[\frac{d}{dt} p(t^*) \right]$$

Model veracity

An efficient predictive model should be veracious, i.e. accurate, precise, and trustworthy. To ensure this, the confidence interval for measuring the trustworthiness of the predictive model, the mean absolute percentage error (MAPE) for measuring the accuracy of the predictive model, and the correlation index or the coefficient of determination (R^2) for measuring the precision of the predictive model are applied as follows:

Confidence Interval (CI) 100(1- α)% of $p(t)$

$$\text{upper confidence } \hat{p}(t) + t_{\frac{\alpha}{2}, df} (SE) \text{ interval} =$$

$$\text{lower confidence } \hat{p}(t) - t_{\frac{\alpha}{2}, df} (SE) \text{ interval} =$$

where SE is the standard error of $p(t)$ and df is the degree of freedom.

Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{p(t) - \hat{p}(t)}{p(t)} \right| \times 100$$

where $p(t)$ is the actual value and $\hat{p}(t)$ is the predictive value.

Coefficient of Determination (R^2)

$$R^2 = \frac{\text{Explained Variance}}{\text{Total Variance}}$$

$$= \frac{SSR}{SST}$$

$$= 1 - \frac{SSE}{SST}$$

where $SSR = \sum_{t=1}^n (\hat{p}(t) - \bar{p}(t))^2$ is an explained variation,

$SSE = \sum_{t=1}^n (p(t) - \hat{p}(t))^2$ is an unexplained variation, and

$SST = SSR + SSE = \sum_{t=1}^n (p(t) - \bar{p}(t))^2$ is a total variation.

RESULTS

Here, we present the results from assessing the methodology and compare the output of applying the predictive model to Nordic countries' response to COVID-19 based on either the herd immunity policy or the strict lockdown policy. The interpretation and analysis of the results are provided as follows.

Fundamental statistics

Table 1 reports the basic descriptive statistics for the number of daily COVID-19 cases in Sweden based on the herd immunity policy and the other Nordic countries (Norway, Finland, and Denmark) based on the strict lockdown policy. It was found that the average daily number of infected people in Sweden was approximately 7,895, which is higher than Norway (3,909), Denmark (3,882), and Finland (2,000). Skewness of [-0.5, 0.5] indicates that the data is symmetrical whereas [-1.0, -0.5] or

[0.5, 1.0] indicates that the data is negatively or positively skewed, respectively. Meanwhile, kurtosis equal to, greater than, or less than 3 indicates that the distribution of data is symmetric, heavy-tailed, or light-tailed, respectively. Thus, the distributions of the number of daily COVID-19 cases in Sweden and Finland are positively skewed and light-tailed whereas those for Norway and Denmark are symmetric and light-tailed.

Table 1. Fundamental statistics for the total COVID-19 cases in Nordic countries.

Descriptive statistics	Sweden	Norway	Finland	Denmark
Mean	7895.24	3908.88	1999.98	3881.95
Standard Error	935.01	343.65	221.64	403.98
Median	3700	4284	1240	2201
Mode	1	0	1	0
Standard Deviation	8721.25	3205.36	2067.37	3768.08
Sample Variance	76060219.77	10274376.68	4274037.96	14198460.02
Kurtosis	-0.80	-1.72	-1.18562214	-1.42
Skewness	0.79	-0.03	0.58	0.43
Range	26669	8132	5983	10513
Minimum	1	0	1	0
Maximum	26670	8132	5984	10513
Sum	686886	340073	173999	337730
Count	87	87	87	87

The estimated parameters for the spreading of COVID-19 in Sweden

This section provides the parameters estimated by logistic model under herd immunity policy of Sweden. Effects of perilla meal upon the modification of fatty acid profiles of broiler meat

Figure 1 shows the estimated daily COVID-19 cases in Sweden under the herd immunity policy. The estimated parameters for the logistic model are $p_0 = 105.84689$, $g = 0.0869$, and $C = 30,063.9635$, while the predictive model is

$$p(t) = \frac{30,063.9635}{1 + 283.0326 \exp(-0.0869t)} \text{ for } t \geq 0.$$

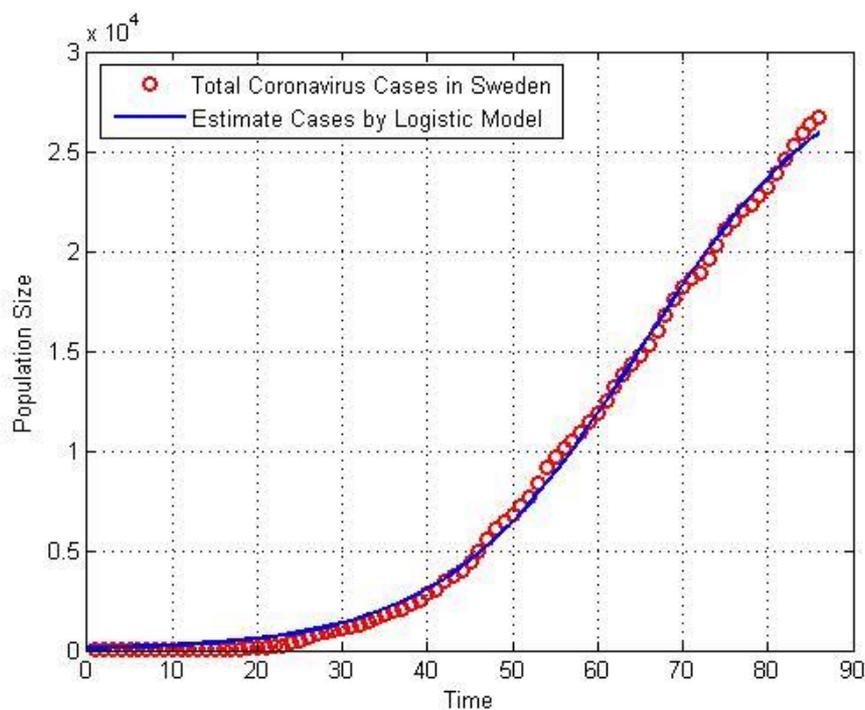


Figure 1. Estimate COVID-19 cases in Sweden under herd immunity policy.

The estimated parameters for the spread of COVID-19 in the other Nordic countries

This section provides the parameters estimated by logistic model under non herd immunity policy (strict lockdown policy or flattened curve policy) of the neighbor countries of Sweden.

Figure 2 shows the estimated daily COVID-19 cases in Norway under the strict lockdown policy. The estimated parameters for the logistic model are $p_0 = 34.4242$, $g = 0.1275$, and $C = 7,815.4299$, while the predictive model is

$$p(t) = \frac{7,815.4299}{1 + 226.0330 \exp(-0.1275t)} \text{ for } t \geq 0.$$

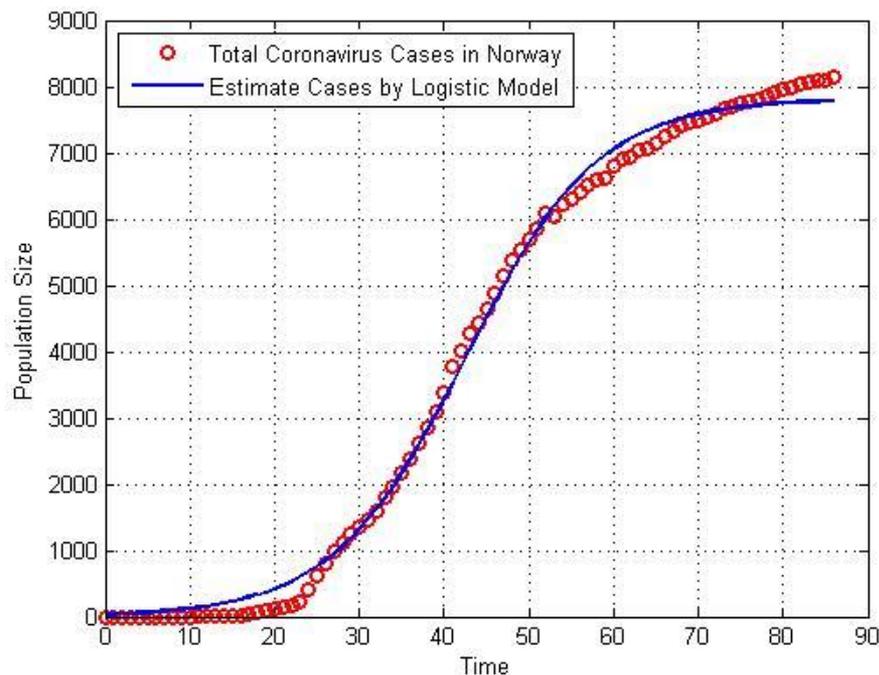


Figure 2. Estimate COVID-19 cases in Norway under strict lockdown policy.

Figure 3 shows the estimated daily COVID-19 cases in Finland under the strict lockdown policy. The estimated parameters for the logistic model are $p_0 = 25.9141$, $g = 0.0931$, and $C = 6,217.9654$, while the predictive model is

$$p(t) = \frac{6,217.9654}{1 + 26.5091 \exp(-0.0931t)} \text{ for } t \geq 0.$$

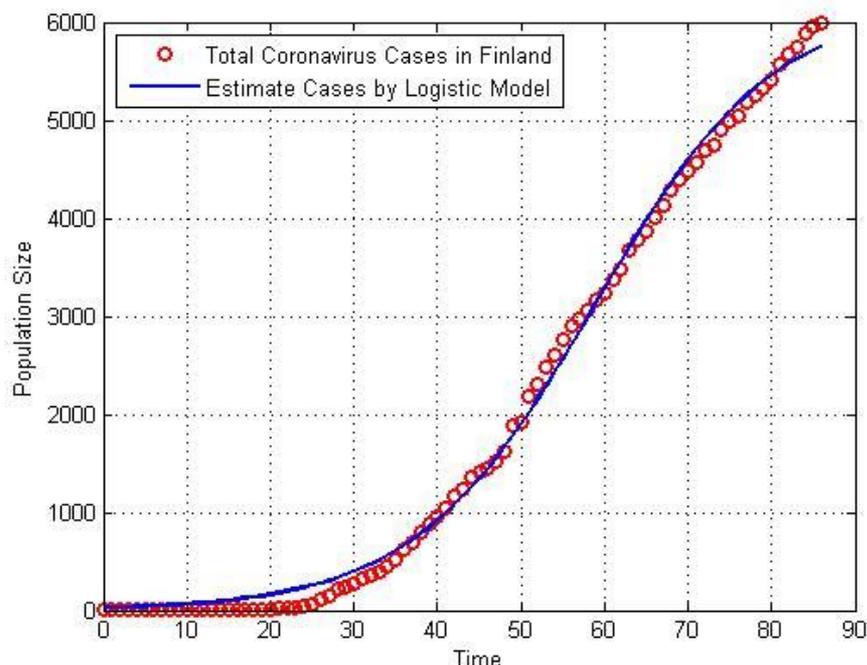


Figure 3. Estimate COVID-19 cases in Finland under strict lockdown policy.

Figure 4 shows the estimated daily COVID-19 cases in Denmark under the strict lockdown policy. The estimated parameters for the logistic model are $p_0 = 45.3325$, $g = 0.1002$, and $C = 10,480.2114$, while the predictive model is

$$p(t) = \frac{10,480.2114}{1 + 230.1853 \exp(-0.1002t)} \text{ for } t \geq 0.$$

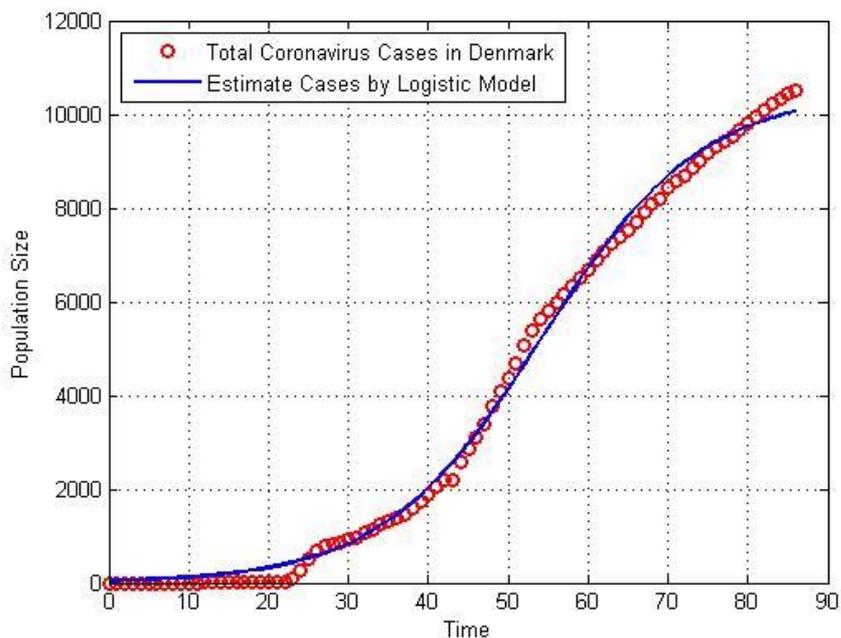


Figure 4. Estimate COVID-19 cases in Denmark under strict lockdown policy.

Results comparison and validation of the predictive models

The results of the behavior and estimated spread of COVID-19 cases in the Nordic countries are shown in Table 2 and Figure 5, respectively.

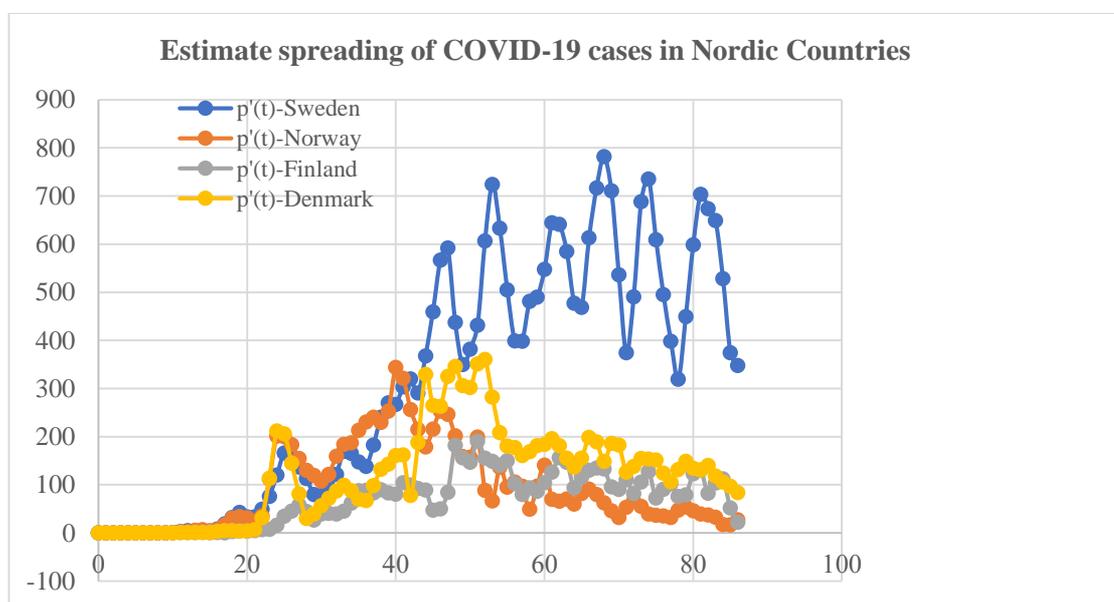


Figure 5. Estimate the derivative of COVID-19 cases in Nordic countries.

Table 2. Statistics for behavior of COVID-19 spreading in Nordic countries.

Countries	Population	Carrying Capacity (%)	Peak time (th day)	Maximum growth rate (cases/ day)
Sweden	10,090,653	30,063.96(0.29)	64.94	653.34
Norway	5,415,408	7,815.42(0.14)	42.52	249.03
Finland	5,539,565	6,217.96(0.11)	58.82	144.71
Denmark	5,789,442	10,480.21(0.18)	54.27	262.57

Note: Population as of May 12, 2020.

Table 2 reports the population, carrying capacity, peak time, and maximum growth rate of the COVID-19 spread in the Nordic countries. At this time, all of the countries have already passed the peak time and maximum growth rate. However, the number of infected people in Sweden is the highest. That is to say, the carrying capacity is approximately cases (0.2979%), which is the predicted cumulative COVID-19 infected number in Sweden during the outbreak. However, the total number of COVID-19 cases in Sweden as of 11 May, 2020, is 26,670 (Worldometer, 2020). This means that the number of infected people in Sweden will gradually decline after passing the peak time, as illustrated by the speed of COVID-19 spread in the Nordic countries in Figure 5. It can be seen that the speed of COVID-19 spread in Sweden is the fastest while that in Norway is the slowest after reaching the peak time despite the fact that the speed of COVID-19 spread in Norway was the fastest in the period before reaching the peak time. Moreover, Table 3 demonstrates the validation of the predictive model based on *MAPE*, R^2 , and confidence intervals for the total cases.

Table 3. Validation of the predictive model.

Time	Countries	Total cases		Confidence Interval
		Actual	Estimate	Lower CI – Upper CI
87	Sweden	27,272	2,6210	25,482 - 26,938
	Norway	8,157	7,789	
	Finland	6,003	5,797	
	Denmark	10,591	10,100	
88	Sweden	27,909	2,6493	25,765 - 27,221
	Norway	8,175	7,792	
	Finland	6,054	5,832	
	Denmark	10,667	10,135	
89	Sweden	28,582	2,6758	26,030 - 27,486
	Norway	8,196	7,795	
	Finland	6,145	5,865	
	Denmark	10,713	10,167	
90	Sweden	29,207	27,005	26,277 - 27,733
	Norway	8,219	7,797	
	Finland	6,228	5,894	
	Denmark	10,791	10,196	
91	Sweden	29,677	27,236	26,508 - 27,964
	Norway	8,237	7,799	
	Finland	6,286	5,922	
	Denmark	10,858	10,223	
MAPE(%)	Sweden = 6.22	Norway = 4.91	Finland = 4.56	Denmark = 5.21
R²	Sweden = 0.99	Norway = 0.99	Finland = 0.99	Denmark = 0.99

DISCUSSIONS

The focus of this research is on forecasting the number of daily COVID-19 cases in Sweden, in which the herd immunity policy was implemented, and comparing the results with Norway, Finland, and Denmark, in which the strict lockdown policy was implemented. For the predictive model, the independent variable (time) could almost completely explain the dependent variable (daily COVID-19 cases) because R^2 for all of the countries was approximately 0.99. However, *MAPE* was 6% for Sweden and 5% for the other countries. In Sweden, the daily number of cases gradually increased and the curve after the peak time was not flattened (Figure 1). However, in Norway, Finland, and Denmark, the daily number of cases gradually increased and the curve after the peak time was flattened (Figures 2 and 3). In Figure 5, the speed of the daily COVID-19 cases in Sweden fluctuated during the outbreak because the strict lockdown policy was not instigated by the government. When estimating the daily COVID-19 cases, the herd immunity policy applied in Sweden did not result in smoothing of the predictive curve after the peak time whereas the strict lockdown policy in Norway, Finland, and Denmark did. However, the number of infections and deaths from COVID-19 in Sweden is still fewer than in other countries in Europe that applied the strict lockdown policy, such as Russia, Italy, and Spain. Therefore, herd immunity policy is an alternative for controlling COVID-19 and can be applied with other methods such as using the lockdown policy in specific high-risk areas for reducing and alleviating the number of deaths from COVID-19.

CONCLUSIONS

The predictive model suggested in this paper for estimating the daily COVID-19 cases in Nordic countries is the logistic growth curve. Sweden is the only country using the herd immunity policy for controlling the spread of COVID-19, while the other Nordic countries (Norway, Finland, and Denmark) are using the strict lockdown policy. The findings from this study indicate that after the peak time, the logistic growth curve for Sweden was not flattened whereas that for Norway had already flattened and those for Finland and Denmark started flattening due to implementing the strict lockdown policy; the number of infectious people in all of the countries started to slow after the peak time, but this was slower in Sweden than in the other countries. To sum up, the herd immunity policy is an alternative for controlling the disease because it does not affect the economy as harshly and could be efficient at flattening the predictive curve for COVID-19 if it is used together with strict lockdown in high-risk areas such as elderly care homes.

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Chiang Mai University Journal of Natural Sciences [ISSN 16851994]

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