A Novel Ensemble Machine Learning and an Evolutionary Algorithm in Modelling the COVID-19 Epidemic and Optimising Government Policies

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***Abstract*—The spread of the COVID-19 disease has prompted a need for immediate reaction by governments to curb the pandemic. Many countries have adopted different policies and studies are performed to understand the effect of each of the policies on the growth rate of the infected cases. In this paper, the data about the policies taken by all countries at each date, and the effect of the policies on the growth rate of the pandemic are used to build a model of the pandemic's behaviour. The model takes as input a set of policies and predicts the growth rate of the pandemic. Then, a population-based multi-objective optimisation algorithm is developed which uses the model to search through the policy space and finds a set of policies that minimise the cost induced to the society due to the policies and the growth rate of the pandemic. Because of the complexity of the modelling problem and the uncertainty in measuring the growth rate of the pandemic via the models, an ensemble learning algorithm is proposed in this paper to improve the performance of individual learning algorithms. The ensemble consists of ten learning algorithms and a meta-model algorithm that is built to predict the accuracy of each learning algorithm for a given data record. The meta-model is a set of Support Vector Machine (SVM) algorithms that is used in the aggregation phase of the ensemble algorithm. Because there is uncertainty in measuring the growth rate via the models, a landscape smoothing operator is proposed in the optimisation process which aims at reducing uncertainty. The algorithm is tested on open access data online and experiments on the ensemble learning and the policy optimisation algorithms are performed.**

***Index Terms*—Epidemiology COVID-19, Policy-making, Evolutionary Algorithms, Ensemble Learning, Optimisation.**

I. Introduction

IT is a great challenge for governments around the world to find the optimal policies to curb the spread of the pandemic. Stricter measures can control the pandemic, thus reducing the number of cases and deaths, at the cost of high economic impact. In this sense, it is crucial to develop methods that can find the optimal policies that reduce the number of cases with a minimal economic impact on society. Developing such methods requires the design of algorithms that can predict the evolution of the pandemic as it allows governments to develop strategic planning to curb the effects. In order to find the optimal government policies against the spread of the virus, in this paper, we propose an evolutionary algorithm that searches through different policies and finds the best policy that minimises the spread of the virus and the cost imposed on society.

In order to implement the optimisation algorithm, there should be a model of the epidemic that can take as input the policies (optimisation parameters) and produce as output the spreading rate of the virus. This model is to be used as the fitness function for the optimisation algorithm. To build such a model, an ensemble learning algorithm is proposed in this paper.

One challenge in using optimisation algorithms via surrogate models is the uncertainty in the fitness evaluation. Known as approximation uncertainty, this type of uncertainty occurs when a model is used to approximate or estimate the fitness function [1]. Such uncertainty affects the optimisation process and should be managed. Because there is uncertainty in the evaluated value of growth rate due to a set of policies, we propose landscape smoothing operators for fitness evaluation of the optimisation algorithm. The proposed method removes high fluctuations in the fitness evaluation process that are usually due to uncertainty.

A. Previous Work

Ensemble learning improves the performance by combining algorithms that complement one another [2]–[5]. The ensemble improves performance by providing diversity and accuracy [6]. In order to reach diversity, two main approaches called Heterogeneous and Homogeneous are usually employed. Diversity is achieved if a set of classifiers are used that misclassify different instances [7]. In Homogeneous approaches, the randomness is injected into the training phase of the classification, which is achieved by methods like manipulating the feature set or the learning algorithms. Among these approaches are Bagging [8] in which the distribution of the training data is changed to achieve different training sets, random subspace [9] which randomly selects subsets of features to build diversity and the diversification of algorithm parameters scheme in which the diversity is incorporated into the learning algorithms [10].

In ensemble learning, two main approaches are the Bagging [11] and AdaBoost [12] algorithms. In order to achieve diversity, these two approaches strategically generate classifiers by manipulating the training data. Bagging approaches perform this by using different datasets. Theoretical study

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of bagging approaches can be found in [13], [14]. In [15], a variation of Bagging for large datasets is proposed which is called *Pasting small votes*. Two versions of these algorithms were proposed, one which is called *Rvotes* creates the data subsets at random and the other, called *Ivotes* creates consecutive datasets based on important data instances that promote diversity. An approach called attribute bagging is proposed in [16] which is a wrapper algorithm and establishes an appropriate attribute subset size. The bootstrap sampling is integrated in [17] with more advanced methods of feature selection which are based on an evaluation of the relationship between the features and the target class. In order to improve the performance of the Bagging algorithm, a method is introduced in [18] that considers the diversity of classification margins in feature subspaces. To do so, the task is converted into an optimisation problem of finding the best weights of feature subspaces.

Dynamic classifier selection and classifier fusion are two main approaches that are used in the literature. Dynamic classifier selection approaches try to predict the accuracy of the classifiers to choose the output of what classifier should be used as output. In classifier fusion methods the output of classifiers is aggregated to reach a consensus.

Ensemble approaches have been used in a number research to tackle the COVID-19 problems. In [19], an ensemble deep learning algorithm is proposed for the detection of COVID-19 via CT images. An automatic detection of COVID-19 via X-ray images is presented in [20] which utilises an ensemble of deep CNN. An ensemble of learning algorithms is used in [21] to diagnose COVID-19 cases via routine blood test. To study vaccine efficacy trials, in [22] an ensemble learning algorithm is adopted. An optimisation algorithm is proposed in [23] to build a sparse ensemble algorithm to predict the evolution of COVID-19.

Machine learning algorithms have been used in some research to build models of the pandemic. An ensemble empirical mode decomposition is proposed in [24], which is combined with ANN to predict the pandemic. In another work [25], in order to predict the pandemic in Egypt, statistical and AI-based approaches are combined. In this work, ARIMA and Non-linear Auto-Regressive Artificial Neural Networks (NARANN) are integrated. In [26], an ensemble of neural networks is presented to build a model of the pandemic in Mexico. Then a fuzzy logic system is employed to reach consensus among the response of these neural predictors. Neural Networks with Long-Short Term Memory networks are combined in [27] to build a model to forecast the pandemic. In [28], some neural network forecasting methods including Multi-Layer Perceptron, Neural Network Auto-Regressive, and Extreme Learning Machine are used to study the effectiveness of public health measures on the epidemic. The model is used to predict the number of active, confirmed, recovered, death and daily new cases in Jakarta and Java. A machine learning-based time series prediction model using the FbProphet model is used in [29] to predict the epidemic curve in Brazil, Russia, India, Peru, and Indonesia. In [30], several regression analysis models are used to analyse the epidemiological data of Egypt and predict the pandemic trend. A cloud computing platform is used in [31] to develop a machine learning algorithm that predicts the threat of COVID-19 cases in countries worldwide. The system provides a real-time prediction of the growth behaviour of the epidemic. In [32] a meta-analysis of the current state-of-the-art of the AI approaches to tackle COVID-19 is presented. A random forest model is used in [33] to estimate the number of cases in 190 countries. A comprehensive review of the recent research on the applications of AI in battling against COVID-19 can be found in [34].

While these research show promising results in modelling the pandemic, they do not take the set of government policies as the input for the models. In this sense, these modelling algorithms do not approach the problem of using the models to find an optimal set of policies to reduce the number of positive cases. The current paper targets the modelling of the behaviour of the pandemic with the aim of providing a practical approach for policy makers.

The rest of this paper is organised as follows. The proposed ensemble learning algorithm is discussed in section II. Section III describes the optimisation algorithm proposed in this paper. Experimental studies are performed in section IV and finally section V concludes the paper.

II. The Proposed Ensemble Learning Algorithm

In this paper, we build a model of the pandemic to predict the growth rate for a given set of policies. Then an evolutionary algorithm is used to search through the set of all policies to minimise the growth rate and the cost induced to society. For many reasons the task of modelling the behaviour of the pandemic is very hard for the existing modelling algorithms. First, the behaviour of the pandemic is very complicated which is affected by a huge number of unpredictable factors. This paper tries to model the behaviour of pandemic based on government policies. Surely there are many other factors that affect the behaviour of the pandemic and are extremely hard to take into account when building the models. Some examples include cultural factors, existing immunities within the societythe density of population, age demography, etc. Second, the data are not complete, many countries do not collect data, and it is almost impossible to know the true number of cases in a country. This is because testing is costly and a significant number of cases remain asymptomatic thus undetected. In this respect, there is a need to improve the performance of the algorithms to better predict the growth rate.

One inevitable consequence of using surrogate models to evaluate the solutions is the uncertainty they suffer from in the estimation of the growth rate. Reducing this uncertainty is crucial as it can mislead the search process. There is much research on how to manage such uncertainty [35]. Most of these works use different averaging techniques to reduce the noise by re-sampling the fitness function several times. In our problem, however, recalculating the growth-rate via the model would not reduce the uncertainty as the modelling algorithms produce deterministic values.

To overcome these challenges, we propose an ensemble algorithm in this paper. Ensemble algorithms usually improve the performance of individual learning algorithms by benefiting from the advantages of base-learners. Using many learning algorithms instead of one not only improves the performance in terms of accuracy but also injects diversity into the output of the models, which is required in the noise reduction process.

Ensemble learning is when multiple learning algorithms are combined to solve a problem. In this paper, we propose an ensemble algorithm to model the data. The base learning algorithms used in the proposed ensemble algorithm are Feed-forward Neural Network (FNN), Radial Basis Network (RBN), Learning Vector Quantisation Neural network (LVQ), Probabilistic Neural Networks (PNN), Exact Radial Basis Network (RBE), Cascade-Forward Neural Network (CFNN), Pattern Recognition Network (PRN), Function Fitting Neural Network (FFNN), Generalised Regression Neural Network (GRNN) and K-Nearest Neighbour (KNN). For all these algorithms, the Matlab 2016a implementations are used. Unless specifically mentioned, the default parameters of the algorithms are used. For FNN, the number of hidden layers is set to 1, with 20 hidden nodes, for RBN, GRNN and PNN, the spread parameter is set to 0.5, for LVQ, the number of nodes in the hidden layer is set to 10 and the number of epoch to 50, for CFNN the number of nodes in the hidden layer is set to 10, for FFNN the number of hidden nodes is set to 30 and for KNN the number of neighbours, k is set to 5.

In the proposed algorithm, the accuracy of the base-learners is estimated via a meta-learning algorithm and a final results among the base learning algorithms is achieved based on the estimated accuracy of these algorithms. The proposed meta-learning algorithm consists of a number of Support Vector Machine (SVM) algorithms that are trained to model the accuracy of each base-learner. A pairwise comparison between the accuracy of each algorithm for each data record is performed and for each pair of base-learners, an SVM is trained to predict for which data records, each of the learners will outperform the other. These set of SVMs provide By combining a number of learning algorithms, the proposed ensemble algorithm outperforms the individual base-learners. The accuracy of each base-learner is modelled based on the data in the training set.

Figure 2 in supplementary materials presents how is some regions in the feature space one algorithm outperforms another one. This suggests that there are some regions in feature space in which one algorithm outperforms other algorithms. If for a particular data point the performance of the learning algorithms is predicted, then in the aggregation step the output of the algorithm with better performance is better to be used as the final output of the ensemble algorithm.

In building an ensemble of classifiers, diversity should be achieved, and it is achieved when a set of classifiers are used that misclassify different instances [7]. In an ensemble of modelling algorithms, diversity is achieved if there are instances for which each algorithm outperforms the others. As presented in figure 2 in supplementary materials, when comparing two learning algorithms on test data, there are instances that GRNN outperform KNN and there are instances that the opposite occurs. In order to show the diversity in the base learners in this paper, table I performs a pairwise comparison between the algorithms to show in what percentage of instances each algorithm outperforms the other. In this table, the number at a cell shows the percentage of the times in which the learning algorithm labelling the column outperforms the learning algorithm that labels the row. That is, for example, in 47.96% of times LVQ outperforms RBN and in 52.04% of times, the opposite happens. In order to generate these data, the modelling algorithms are used to predict the growing rate of the pandemic for all the test data records. Then, to compare two learning algorithms, the outputs of the two learning algorithms for each data record are compared and the percentage of the data records for which a learning algorithm performs better than the other is reported in the table. The data for all countries except the UK are used to train the learning algorithms and the data for the UK are used to test. The data are averaged over 50 independent runs, where for each run the learning algorithms are trained and tested independently.

In some cases, some learning algorithms perform much better than some others, for example, in 71.95% of the times LVQ outperforms PNN. Note that although in majority of times one algorithm outperforms the other one, a smart ensemble of these algorithms can improve the performance further. It can be achieved by knowing in what cases which algorithm provides better prediction.

In order to study if SVM is capable of identifying where in the feature space each learning algorithm outperforms the other one, table II shows the performance of SVM in predicting the performance of the learning algorithms. The data shows the accuracy of SVM in predicting which of the algorithms performs better for test data in a pairwise comparison. To generate these data, the data for all countries are divided into 1/2 training, X and 1/2 testing data, T. The training data X are used to train the 10 classifiers used in this paper. The testing data, T are then split into 2/3, W for training the SVMs and 1/3, V testing the SVMs. For each pair of classifiers, an SVM is trained to predict for which data records which of the algorithms outperforms the other. To do so, the learning algorithms are tested on W and a pairwise comparison is performed on the performance of all the learning algorithm on all the data records in W. Then an SVM is trained on the pairwise comparison on all the data in W to learn which of the learning algorithm outperforms the other one for each of the data records. This way, the SVM is trained to learn where in the feature space which of the algorithms performs better. The SVMs are then tested on the data V and the results are reported in the table. The data are averaged over 50 independent runs, where the sets X, T, W and V are chosen independently randomly for each run.

As presented in table II with very good accuracy, SVM is capable of predicting which algorithm performs better. When using an ensemble of learning algorithms, having a prediction of which of the algorithms is more likely to provide more accurate results can help to decide the output of which of the learning algorithms is better to be used as output.

The idea in the proposed ensemble method is that different learning algorithms perform differently in different regions in the feature space. Therefore, for a given data point, the per-

	RBN	LVQ	PNN	RBE	CFNN	PRN	FFNN	GRNN	KNN	FNN
RBN	-	47.96	51.49	52.08	47.76	10.86	38.17	58.58	60.07	67.91
LVQ	52.04	-	28.05	66.56	58.84	20.29	30.21	58.47	60.35	64.28
PNN	48.51	71.95	-	66.79	59.33	13.99	34.33	61.77	61.94	66.84
RBE	47.92	33.44	33.21	-	58.21	27.16	32.46	61.57	62.31	68.66
CFNN	52.24	41.16	40.67	41.79	-	21.56	27.99	61.19	60.45	69.03
PRN	89.14	79.71	86.01	72.84	78.44	-	63.02	66.43	65.14	66.89
FFNN	61.83	69.79	65.67	67.54	72.01	36.98	-	69.4	70.15	75.37
GRNN	41.42	41.53	38.23	38.43	38.81	33.57	30.6	-	64.18	63.02
KNN	39.93	39.65	38.06	37.69	39.55	34.86	29.85	35.45	-	64.93
FNN	32.09	35.72	33.16	31.34	30.97	33.11	24.63	36.98	35.07	-

TABLE I
A PAIRWISE COMPARISON BETWEEN THE LEARNING ALGORITHMS. THIS SHOWS THE PERCENTAGE OF TIMES AN ALGORITHM PERFORMS BETTER THAN THE OTHER. THIS IS WHERE THE DATA FOR ALL COUNTRIES ARE USED FOR TRAINING AND THE DATA FOR UK ARE USED FOR TESTING. THE DATA ARE AVERAGED OVER 50 RUNS.

	RBN	LVQ	PNN	RBE	CFNN	PRN	FFNN	GRNN	KNN
LVQ	89.25	-	-	-	-	-	-	-	-
PNN	89.29	97.33	-	-	-	-	-	-	-
RBE	86.74	87.34	87.61	-	-	-	-	-	-
CFNN	74.53	78.71	79.06	78.78	-	-	-	-	-
PRN	90.48	91.6	91.12	91.44	92.72	-	-	-	-
FFNN	76.95	79.18	79.1	80.98	64.52	90.94	-	-	-
GRNN	80.94	83.14	83.12	83.75	64.42	94.68	72.55	-	-
KNN	81.21	82.78	82.96	83.68	63.29	94.42	71.21	67.01	-
FNN	79.02	78.08	77.99	78.69	59.64	93.23	66.13	66.31	65.09

TABLE II
THE PERFORMANCE OF SVM IN PREDICTING THE ACCURACY OF THE LEARNING ALGORITHMS. THE DATA ARE AVERAGED OVER 50 RUNS.

formance of the algorithms at the data point is estimated, and the output of the algorithm with higher estimated performance can be chosen as the output. In the proposed algorithm, we use a number of learning algorithms to model the growth rate of the epidemic. Then, we use the SVM algorithm to model the performance of the algorithms in different regions.

The proposed ensemble learning method is presented in algorithms 1. A description of the proposed algorithm is as follows. First, the data are divided into training and testing sets. In steps 2 to 12, the training set is used to build a model that predicts the performance of different learning algorithms in different regions in the feature space. In step two, the training data are partitioned into four subsets. Three of the partitions are used as training and one partition as the test set. This is performed in a round-robin manner (the for a loop at step 3), so all the data are used as test set once. Then all the base learners are trained, tested, and the results are stored $L_l(X_k^i)$. Comparing the base learners based on $L_l(X_k^i)$ gives an indication of the accuracy of each of the learning algorithms for the data point X_k^i. In steps 7-9, a pairwise comparison between the learners is performed and a dataset, Y, is built that stores information about which of the learners performs better for a particular data record. In steps 10-12, an SVM is trained for each pair of learners that models where in the feature space each learner performs better. In step 13, the training data are used to train the base learners.

In the testing phase of the algorithm, in step 2, the output of all the base learners for the input data, T_k are measured and stored in Z_{kl}. Then, the algorithms that are more likely to produce a more accurate result for the T_k are identified. To do

begin
1. Divide the data into train and test sets
2. Partition the train set, X into four partitions of equal size, X^i, $i = 1\ldots4$
3. For $i = 1 \rightarrow 4$
   begin
4. For $l = 1 \rightarrow |L|$ train the l-th modelling algorithm, L_l, using $\bigcup_{\forall j \neq i} X^j$
5. For $l = 1 \rightarrow |L|$
6. For $k = 1 \rightarrow |X^i|$ find the output of L_l for X_k^i, $L_l(X_k^i)$
7. For $l = 1 \rightarrow |L|$
8. For $m = l+1 \rightarrow |L|$
9. If $L_l(X_k^i)$ is more accurate than $L_m(X_k^i)$, $Y_{kml}^i = 1$, else $Y_{kml}^i = 0$
   end
10. For $l = 1 \rightarrow |L|$
11. For $m = l+1 \rightarrow |L|$
12. Train an SVM, S_{ml} with $\bigcup_{i=1}^4 X_{ml}^i$ as input and $\bigcup_{i=1}^4 Y_{ml}^i$ as output
13. For $l = 1 \rightarrow |L|$ train L_l using X

end

Algorithm 1: The training phase of the proposed ensemble algorithm

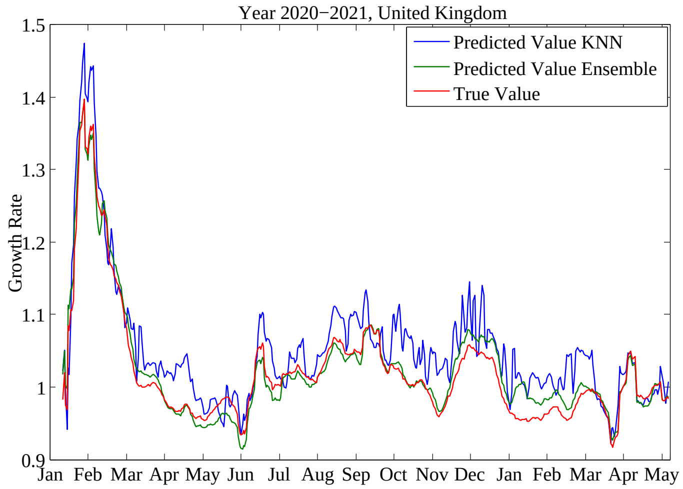

Fig. 1. The predicted and true values of growth rate of the number of cases in the UK using KNN and the proposed ensemble algorithm. These data are generated by using all the data except the data for the UK to train the models. Then the model is tested on the UK data.

begin
1. For $k = 1 \rightarrow |T|$
   begin
2. For $l = 1 \rightarrow |L|$ find the output of L_l on test record T_k and store it in Z_{kl}
3. For $l = 1 \rightarrow |L|$ $C_{kl} = 0$
4. For $l = 1 \rightarrow |L|$
5. For $m = l+1 \rightarrow |L|$
6. If output of S_{ml} on T_k, $S_{ml}(T_k) = 1$, $C_{km} = C_{km} + 1$, else $C_{kl} = C_{kl} + 1$
7. Return $\frac{\sum_{l=1}^{|L|} Z_{lk} C_{lk}}{\sum_{l=1}^{|L|} C_{kl}}$ as the output for test record T_k
   end
end

Algorithm 2: The testing phase of the proposed ensemble algorithm

so, in steps 2-6, based on the trained SVMs that model the comparison between each pair of the algorithms, the number of times each learner is predicted to perform better is counted and stored in C_{kl}. Then in step 7, C_{kl} is used as a weight to measure the weighted average of the output of the base learners, Z_{kl}.

By estimating the accuracy of each of the modelling algorithms via SVMs, and performing the weighted averaging, our proposed algorithm manages the uncertainty in objective evaluation.

Figure 1 shows the growth rate of the new cases in the UK and its predicted value with the proposed ensemble learning and the KNN algorithms. The data for other countries are used to train the learning algorithm and the model is used to predict the values for the UK. The data in this figure suggest that not only the proposed algorithm performs better in modelling the growth rate, but also, compared to KNN, there are fewer fluctuations in the predicted value. This is true when the proposed algorithm is compared with other base learning algorithms. The reason here is that the proposed algorithm performs a weighted averaging to aggregate the output of the classifiers and this averaging reduces the uncertainty (Note that the main approach in managing uncertainty in fitness calculation is averaging [35]).

III. The Proposed Optimisation Algorithm

The aim of this paper is to propose a method that uses the existing data about the behaviour of the pandemic and suggests the best policy to the decision-makers. This process consists of two parts; one is the machine learning algorithm that models the behaviour of the pandemic and the other is the optimisation process that searches through different policies and suggests the policy with the lowest cost and best effect on the growth rate of infected cases. In this section, we propose the optimisation process. Here we face a multi-objective optimisation problem, one criterion is the growth rate in the infection rate, and the other is the cost it induces on the society. Although the growth rate of the pandemic is straightforward, the cost each policy induces on the society is tough to measure. Therefore, in this paper, we consider three scenarios for the optimisation process.

The first scenario is when the policymakers have a good estimation of the cost posed by each policy to society. In this scenario, there is a two objective optimisation problem of minimising the growth rate and the cost of policies to society. In this scenario, the cost of the policies is simply calculated as,

$$f = \sum_{i=1}^{|P|} g_i(x_i), \tag{1}$$

where $g_i(x_i)$ is the cost of implementing P_i as suggested by x_i. For example, as shown in table III in supplementary materials, x_1 can take a value between [-100,100] and $g_1(x_1)$ returns the cost of implementing P_1 with the value x_1. Note that in the first scenario, it is assumed that $g_i, i = 1...|P|$ are known.

Although it is reasonable to assume that a government can make a good estimation of these costs, it is understandable that many governments may not have such measurements. To overcome this, we suggest the second scenario in which the estimated cost of each policy is not required, but the policy-maker should rank the policies based on the cost they believe will inflict on society. In this case, the cost of a set of policies is calculated as,

$$f = \sum_{i=1}^{|P|} \left(\frac{x_i - \min_{x_i}}{\max_{x_i} - \min_{x_i}}\right) r_i, \tag{2}$$

where r_i is the rank of the policy P_i and the value of x_i is normalised between [0,1] so the weight of all policies is equal.

The third optimisation scenario does not calculate an aggregate cost of the policies but considers each of the values of the policies x_i as an objective that should be minimised individually. Thus, we have a multi-objective optimisation problem with $|P|+1$ objectives ($|P|$ policies plus growth rate). This scenario is devised, so a set of non-dominated solutions among all policies, and the growth rate is suggested to the policy-makers.

In terms of the optimisation process, the first scenario is the most straightforward problem to solve; however, it requires a good indication of the cost that each policy causes. The second scenario is less straight forward to solve, but easier for the policymakers as there is no need of knowing the true (or estimated) cost of implementing each policy. If the policymakers do not have any indication of the cost each policy causes, the third scenario is used. In this case, because the number of objectives is large (greater than 3), most multi-objective optimisation problems will not work properly. With 21 objectives, the third scenario is a "many-objective optimisation problem" and specialised algorithms are required to solve the problem. Studying the ways in which the problem can be solved via this scenario remains for future work as it requires new sets of algorithm development and experiments. In terms of optimisation process, clearly, this problem is harder to solve than the first and second scenarios. However, this scenario is used when the governments do not have any indication of the cost that each policy inflicts on society.

begin
1. Set the algorithm parameters, c_1, c_2, w
2. Initialise the population X, V
3. **While** not termination condition
   begin
4. For $i = 1 \rightarrow |X|$ calculate growth rate of x_i via landscape smoothing
5. For $i = 1 \rightarrow |X|$ calculate cost of x_i to society
6. For $i = 1 \rightarrow |X|$ calculate the fitness of x_i via SPEA2
7. update gbest, pbest
8. For $i = 1 \rightarrow |X|$
   $v_i = wv_i + c_1R(0,1)(pbest_i - x_i) + c_2R(0,1)(gbest - x_i)$
9. For $i = 1 \rightarrow |X|$ $x_i = x_i + v_i$
10. Update the set of non dominated solutions H
   end
end

Algorithm 3: The proposed optimisation algorithm

In step 4 of the algorithm 3, the growth rate caused by the policies suggested by the particle x_i is calculated via the surrogate model. As explained before, figure 1 suggests that due to the averaging nature of the proposed algorithm, some of the uncertainty in calculating the fitness function is removed. However, there still remains some uncertainty in fitness calculation that affect the optimisation process. Some improvements that are observed by the optimisation algorithm may be due to uncertainty rather than real progress. In literature, resampling is the main approach to managing this [35]. Resampling means that fitness is evaluated several times and a sort of averaging is performed. However, due to the deterministic nature of the modelling, resampling cannot be used in this paper. To overcome this, we propose a landscape smoothing operator [36]. In the proposed algorithm, when measuring the fitness of a particular solution, instead of resampling the same solution, the fitness of the points in the landscape close to the solution is used for the averaging operator. The argument is that a small change in policies should not result in a large change in the growth rate and any sudden change in the growth rate is more likely due to uncertainty rather than a true change in the value of the growth rate. The operator we propose in this paper creates a number of solutions in a radius around the current solution and performs an averaging over these solutions. Because these solutions are close to the current solution they should have similar value in fitness and the averaging could remove the uncertainties.

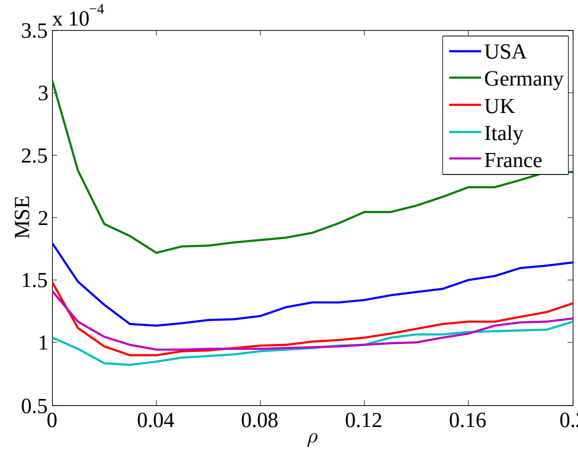

Fig. 2. The performance of the proposed ensemble learning algorithm when the averaging operator is used for different values of radius. This is averaged over all the data records for each country.

Figure 2 shows the performance of the proposed ensemble learning algorithm when the averaging operator is used for different values of the radius. Here, all the dimensions of the feature space are normalised between [0,1] to manage the scaling problem so all the features vary between zero and one. In this method, the uncertainty is reduced by finding a number of solutions (in this case ten solutions) on a hypersphere around the current solution at the radius ρ and find the average value as the estimated growth rate. The data in this figure are averaged over all the data records available for each country. The data in this graph suggest that at the radius around $\rho = 0.04$ (around 4% of the length of the feature space), the algorithm reaches its best performance. At $\rho = 0$, no averaging is performed. This suggests that using an averaging over the solutions in a hypersphere around the solution can remove uncertainty and improve the prediction performance of the proposed algorithm. Because the best performance is achieved at $\rho = 0.04$, in this paper we use this value for uncertainty reduction.

The second operator for reducing the uncertainty uses a characteristic of Particle Swarm Optimization (PSO) in the search process. In PSO, because in each iteration the individuals move a small step in the search space, the change in the fitness should not be large and any sudden change should be smoothed. Figure 3 shows the expected change in the value of growth rate due to the movement operator in PSO for a different number of steps, τ. The data suggest that, on average, the change in the predicted growth rate is small, for

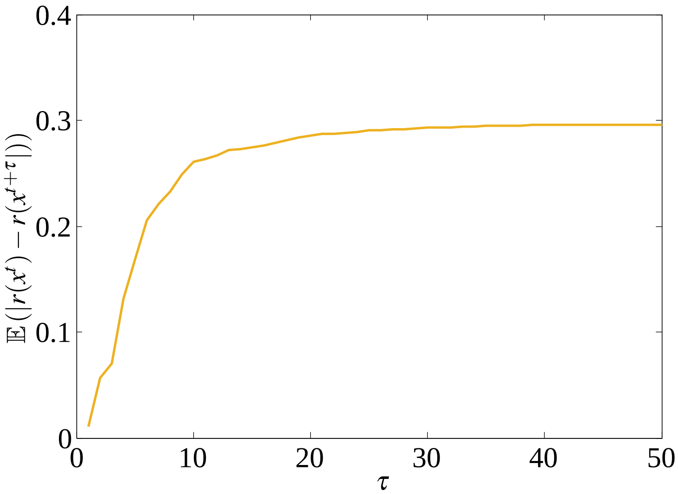

Fig. 3. The expected change in the predicted growth rate, $r(.)$, as a function of the number of steps the PSO takes. This is an average over 50 runs.

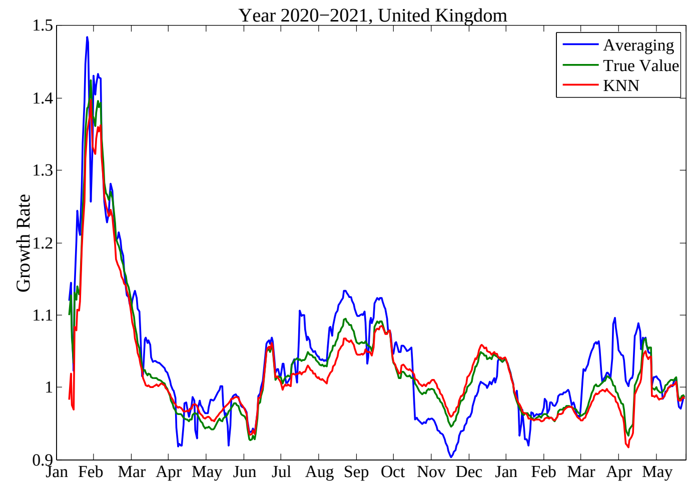

Fig. 4. The proposed Landscape Smoothing operator applied to KNN in predicting the growth rate for USA. Landscape Smoothing operator applies both averaging and movement smoothing operators.

a small number of steps taken by the algorithm. This means that if the algorithm observes a sudden change in the value of the predicted growth rate, with high probability it is due to uncertainty rather than a real change due to the changes in the policies. As the algorithm takes more steps, larger changes in the predicted growth rate are observed.

Thus the growth rate of the particle x_i^t is calculated as,

$$\bar{r}(x_i^t) = \frac{1}{\sum_{j=t-\tau}^{t} e^{j-t}} \sum_{j=t-\tau}^{t} r(x_i^j) e^{j-t}, \tag{3}$$

where $r(x_i^t)$ is the growth rate of i-th particle at iteration t, and $\bar{r}(x_i^t)$ is the smoothed value of the growth rate. In other words, the smoothed value of growth rate is the weighted average of the growth rate over the last τ steps the particle has taken in the search space. The weight of the growth rates in previous steps decay exponentially with the time difference, so the values of growth rate in near past have exponentially greater weight than ones in distant past. This has been devised because the more distance between two points in the search space the less correlation is expected between the fitness of the points (see figure 3.

In order to show how the proposed smoothing operator removes the fluctuations in the fitness landscape that are due to approximation uncertainty, figure 4 shows the proposed Landscape Smoothing operator applied to smooth the predicted value of the growth rate for the KNN algorithm. While KNN may show sudden changes in the predicted value, the proposed smoothing operator reduces the fluctuations. Removing the fluctuations has two benefits; first, it decreases the error in the prediction. Second, it removes the rapid changes in the predicted value that are due to the approximation uncertainty that can mislead the optimisation algorithms. When the algorithms observe a large change in the fitness function, they are affected and change the search direction accordingly. In the case of PSO for example, when a particle observes an improve in the value of the fitness, it stores the particle in its *pbest* variable. If this improvement is due to uncertainty, then the particle will stick to this solution and will keep following this value. Thus, removing these rapid changes is crucial in the optimisation process.

In step 5 of the algorithm, the cost of the set of policies x_i is calculated. The cost can be measured via any of the three scenarios mentioned before. In step 6, Strength Pareto Evolutionary Algorithm 2 (SPEA2) [37] is used to measure the fitness of each solution. If the first or the second scenario are used, we have a two-objective optimisation problem, one objective is the cost and the other is the growth rate. If the third scenario is used, we have a 21 objective-optimisation problem, 20 of which correspond to the policies summarised in table III in supplementary materials and one is the growth rate.

In step 8 of the algorithm, the PSO optimisation is performed via the following equation.

$$v_i = wv_i + c_1 R(0,1)(pbest_i - x_i) + c_2 R(0,1)(gbest - x_i), \tag{4}$$

$$x_i = x_i + v_i. \tag{5}$$

where c_1 and c_2 are positive constants, $R(.,.)$ is uniform random number generator, w is the inertia weight, and pbest is the local and gbest is the global best solutions [38].

IV. Experimental Results

In this section, we first study the performance of the learning algorithms in modelling the pandemic based on government policies. We compare the performance of the proposed algorithm to a number of ensemble learning algorithms including STLR [39], CBCA [39], MV [39], ABJ48 [39], RF [39], oRF10.1007, RoF [40] and MPRoF-P [40]. The performance of the learning algorithms in terms of mean square error are summarised in table III. The data are averaged over 20 independent runs. In these experiments, the *leave-one-country-out* scheme is adopted, that is the data for all countries except the test countries are used to train the models and the algorithms are evaluated on the test country. The best performance among the algorithms is achieved by GRNN and KNN algorithms. The worst performance is for PRN and after that RBE. Among the ensemble algorithms, the proposed SVMEL has reached the best performance among the algorithms except for Germany and France. The Friedman rank test is performed on the data and the rank of different approaches is also included in the table. For all the countries presented here, the proposed algorithm has reached the best rank for all the experiments. The same experiments are performed on the data from India and Brazil as the mostly affected countries, China, as the country from which the pandemic started and New Zealand as a country with very effective policies. The data are presented in table I in supplementary materials.

In order to statistically test the proposed algorithm, Kruskal-Wallis and two-tailed Wilcoxon tests are performed in this paper and the data are presented in table IV in supplementary materials. In this table, 'SS' is the sum of squares of each source, 'df' is the degree of freedom associated with each source, 'MS' is the mean squares (the ratio SS/df) and 'Chi-square' is the ratio of mean squares. The p-values represent the the probability that the samples are taken from populations with the same means. The small p-values in this table are small, which indicates that the null hypothesis that all the samples are taken from the same mean is rejected.

Figure 3 in supplementary materials present the box-plot of the results of different algorithms for different countries. A comparison between the base-learners with the ensemble learning algorithms suggest that not only the ensemble algorithms reach better performance, but also, with a smaller standard deviation the results are more consistent. This is the case for the experiments on France, USA and United Kingdom. For Germany, the standard deviations for the base-learners and the ensembles have similar values.

The predictions offer good results, suggesting the data from the countries around the world can be used to predict the behaviour of the pandemic in another country, which means that the response of the pandemic behaviour to policies is very similar in different countries.

In order to compare the performance of the proposed SVMEL with the base learning algorithms and other ensemble algorithms, table IV shows the performance of different learning algorithms averaged over all the countries. To generate these data, the algorithms are tested on all the countries and the average MSEs are reported. For each country, the training data are created to contain the data for all the countries except the testing country. The last column shows the Friedman rank test. Among the algorithms, the proposed algorithm reaches rank first, followed by RoF and MPRoF-P.

Figure 5 shows the Pareto front for the first scenario found by the proposed optimisation algorithm when the proposed ensemble method is used for predicting the growth rate. Because we did not have access to the data estimating the cost of each policy to the society, in this experiment, we set an example of costs in table V. Note that the costs are different in different countries, so the policy-makers should use their own cost table.

In this paper we compare a number of optimisation algorithms. The parameters of the optimisation algorithms are set as GA [41] (mutation rate=0.05, crossover rate 0.7), PSO [42] (c_1=2, c_2=2, w=0.1), Evolutionary Programming (EP, parameters set st [43]), Fast Evolutionary Programming (FEP, parameters set as [44]), Evolutionary Strategy (ES, parameters set as [45]), Fast Evolutionary Strategy (FES, L=1, S=1.1) [46], Ma-ssw-chains (MASSW, parameters set as [47]) and Differential Evolution (DE, F=0.2, O=0.8). In order to compare the performance of different optimisation algorithms, table VI shows the mean hyper-volume of the Pareto-front for the first scenario optimisation with the cost of each policy presented in table V. The Friedman rank test suggests that PSO achieves the best performance among the optimisation algorithms and its performance is improved when the landscape smoothing operator in equation 3 is used. For all the algorithms we use the averaging operator with $\rho = 0.04$ to reduce the uncertainty with 10 samplings. That is, when estimating the growth-rate for a solution, 10 solutions at a radius $\rho = 0.04$ around the solutions are generated randomly and an averaging is performed.

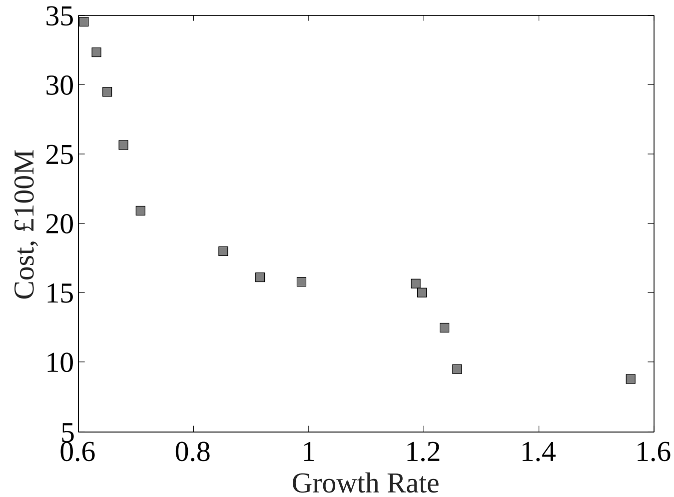

Fig. 5. The pareto front of the policies achieved by the proposed algorithm. The costs are in £100M and the cost of each policy is assumed as table V.

For the third scenario, the algorithm returns the Pareto-front where each policy is considered as an objective. Table VII shows eight of the solutions in the Pareto-front. These are non-dominated solutions and the policy-makers should choose a policy from this list. When the estimated cost of each policy to the society is unknown, or for some cases like closing the schools is hard to estimate, the policy-makers should choose from these values subjectively. For example, if the goal is to minimise the growth rate at any cost without closing schools, a solution with minimum growth-rate that suggests opening school can be used.

V. Conclusion

In this paper, we proposed an evolutionary algorithm with a surrogate ensemble learning algorithm that performs as a fitness function to find the optimal government policy against the spread of the virus. We used data about the policies taken by 183 countries and the data about the number of

		USA		GERMANY		UK		Italy		France	
	Classifier	Mean MSE	Rank	Mean MSE	Rank	Mean MSE	Rank	Mean MSE	Rank	Mean MSE	Rank
Base Learners	RBN	5.552e-03	13.5	3.492e-03	15	2.786e-03	13.7	2.123e-03	10.4	2.418e-03	14
	LVQ	6.397e-03	15.1	3.925e-03	16.5	3.321e-03	15.3	2.316e-03	12	2.821e-03	15.8
	PNN	6.410e-03	15.1	3.922e-03	16.5	3.321e-03	15.3	2.312e-03	12	2.831e-03	15.8
	RBE	6.465e-03	16.6	3.942e-03	18	3.342e-03	16.8	2.337e-03	13.5	2.855e-03	17.4
	CFNN	4.493e-03	14.2	1.825e-03	8.9	3.676e-03	13.9	2.462e-03	15.4	1.624e-03	7.7
	PRN	6.700e-04	18.2	6.899e-04	19	8.774e-04	19	7.538e-04	18.5	7.231e-04	19
	FFNN	1.128e-02	12.6	1.577e-03	7.5	1.737e-03	11	5.598e-03	16.2	1.908e-03	9.4
	GRNN	2.106e-03	10.7	1.669e-03	7.3	1.870e-03	11.1	2.642e-03	14.7	1.413e-03	6
	KNN	2.306e-03	11.7	1.731e-03	8.5	2.023e-03	12.3	2.751e-03	15.8	1.475e-03	8.3
	FNN	1.355e-02	16.6	1.984e-03	9.9	4.638e-03	16.3	3.978e-03	16.5	2.985e-03	13.1
Ensembles	SVMEL	3.161e-04	1	9.625e-04	2.1	1.808e-04	1	9.892e-04	1	1.478e-04	2.1
	STLR	8.397e-04	7.2	6.543e-04	1	4.945e-04	7.1	1.928e-03	8	4.890e-04	10.8
	CBCA	9.600e-04	9.2	1.514e-03	5.8	3.380e-04	4	1.463e-03	3	2.533e-04	7.2
	MV	7.512e-04	6.1	2.054e-03	12.3	3.760e-04	5	2.242e-03	6	3.722e-04	12.9
	ABJ48	5.368e-04	4	1.052e-03	3.2	2.379e-04	2	7.304e-04	2	2.238e-04	1
	RF	8.821e-04	8.2	2.250e-03	13.5	5.489e-04	8.1	1.648e-03	7	4.152e-04	9.6
	oRF	4.647e-04	3	1.766e-03	9.5	4.341e-04	6	1.089e-03	4	3.027e-04	3.2
	RoF	6.470e-04	5	1.337e-03	4.6	5.966e-04	9.1	1.344e-03	9	5.230e-04	4.8
	MPRoF-P	4.070e-04	2	1.865e-03	10.9	2.668e-04	3	2.118e-03	5	3.215e-04	11.9

TABLE III
THE MEAN SQUARE ERROR OF DIFFERENT LEARNING ALGORITHMS. THIS IS FOR WHEN THE DATA EXCEPT DATA FOR THE UK ARE USED FOR TRAINING AND THE DATA FOR THE UK ARE USED FOR TESTING. THE RESULTS ARE AVERAGED OVER 20 RUNS.

	Classifier	Mean MSE	STD	Rank
Base Learners	RBN	4.383e-03	3.252e-03	12.4
	LVQ	4.786e-03	3.459e-03	13.9
	PNN	4.797e-03	3.467e-03	13.9
	RBE	4.204e-03	3.483e-03	14.2
	CFNN	1.201e-02	5.229e-02	12.6
	PRN	7.720e-02	9.979e-02	18.9
	FFNN	1.187e-02	8.460e-02	12.1
	GRNN	3.689e-03	3.563e-03	11
	KNN	3.803e-03	3.594e-03	11.9
	FNN	2.367e-02	1.364e-01	14.5
Ensembles	SVMEL	7.538e-04	1.818e-10	1.3
	STLR	1.529e-03	9.271e-10	6
	CBCA	2.031e-03	7.140e-10	9.9
	MV	1.624e-03	8.324e-10	7.2
	ABJ48	1.246e-03	4.965e-10	4.4
	RF	2.366e-03	9.632e-10	12.2
	oRF	1.899e-03	8.433e-10	8.8
	RoF	8.710e-04	1.139e-10	2.3
	MPRoF-P	1.043e-03	9.362e-10	3.3

TABLE IV
THE PERFORMANCE OF DIFFERENT ALGORITHMS AVERAGED OVER ALL THE COUNTRIES. THE DATA FOR ALL COUNTRIES EXCEPT THE TEST COUNTRY ARE USED TO TRAIN THE LEARNING ALGORITHMS. THE COLUMN RANK SHOWS THE FRIEDMAN RANK OF THE ALGORITHMS. MEAN REPRESENTS THE AVERAGE AND STD REPRESENTS THE STANDARD DEVIATION OF THE RESULTS.

Policy	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
Cost	8	1	9	4	6	6	5	9	9	7
Policy	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}
Cost	8	4	4	3	5	6	3	5	7	9

TABLE V
AN EXAMPLE OF THE COST OF EACH POLICY INFLICTED TO SOCIETY IN £100M.

Optimiser	Mean MSE	STD	Rank
PSO+Smoothing	34.64	1.02	1.5
PSO	33.83	1.24	2.2
GA	29.75	0.70	9.2
DE	32.34	0.73	4.3
ES	30.21	1.12	8.4
FES	32.92	0.33	3.1
EP	31.6	0.41	5.7
FEP	28.14	1.02	11.7
MASW	30.75	0.56	7.4
EDA	31.4	0.96	6
RCODE	29.88	0.71	8.9
LLSO	29.17	1.22	10.2

TABLE VI
THE MEAN HYPER-VOLUME (HV) OF THE PARETO-FRONT FOR THE FIRST SCENARIO OPTIMISATION WITH THE COSTS PRESENTED IN TABLE V. MEAN REPRESENTS THE AVERAGE AND STD REPRESENTS THE STANDARD DEVIATION OF THE RESULTS OVER 30 INDEPENDENT RUNS.

cases in these countries to build a model that takes as input the policies taken by a country and generates as output the growth rate of the infected cases. To build this model, we propose an ensemble machine learning algorithm that consists of 10 base learning algorithms. In the proposed ensemble, in order to aggregate the output of the base learning algorithms, SVM is used to predict the performance of each of the algorithms. Experiments performed in this paper suggest an improved performance of the proposed algorithm. We then use this model as a fitness function to build a multi-objective optimisation algorithm.

The proposed algorithm was trained on the data from the beginning of the pandemic, until the 20-th of August, the date of writing of this paper. As time progresses and more data are available, more accurate models can be created and thus more reliable policies are suggested by the proposed algorithm. Also, as more policies are devised by the governments, and more data are available, the accuracy of the models and the suggested policies will improve. At the moment, one

Rate	1.06	0.83	0.84	0.81	1.42	0.93	0.87	0.84
P_1	66	6	87	-18	73	41	-19.39	46.59
P_2	-87	60	70	42	78	66.16	-43.36	13.74
P_3	-77	61	88	53	32	74.82	-100	-51.18
P_4	15	50	49	52	29	14.36	14.28	18.31
P_5	3	3	0	0	2	0.92	0	2.43
P_6	1	0	1	0	0	1	0	0.67
P_7	67	16	93	29	29	76.36	0	42.71
P_8	1	1	0	2	2	2	0.33	1.93
P_9	2	1	0	1	2	1.03	2	1.97
P_{10}	0	1	1	0	1	0.17	0	1
P_{11}	0	0	4	2	0	1.09	4	2
P_{12}	2	0	1	0	1	2	2	1.24
P_{13}	0	1	1	1	1	2	0	0
P_{14}	1	4	1	4	4	0.23	2.24	4
P_{15}	-15	-35	-89	-91	40	-100	33.83	3.59
P_{16}	3	2	3	1	3	1.24	1.27	2
P_{17}	1	2	1	1	1	2.1	2.96	0.84
P_{18}	2	0	2	2	0	0.4	0	1.05
P_{19}	-29	97	-84	12	9	-79.64	-100	48.42
P_{20}	3	1	2	1	3	0	0	3

TABLE VII
SOME OF THE SOLUTIONS IN THE PARETO-FRONT WHEN THE THIRD SCENARIO OPTIMISATION IS PERFORMED.

complication is data availability and accuracy. Not all governments release data about the policies they take. Governments should provide more organised information about their policies and cases. Also, there is noise in the data. The number of cases reported by governments almost never presents the true number of infected cases. One is because of different testing policies between governments. The other is transparency as some countries may not report the true number of cases. Unless these obstacles are removed, the modelling algorithms are destined to suffer from inaccuracy.

Because of the nature of modelling algorithms, the optimisation algorithms should adopt an uncertainty reduction mechanism. In the literature, averaging is usually used to reduce noise. The uncertainty in modelling problems is the approximation uncertainty [1], [48] and because it is deterministic, it cannot be removed via averaging. In this paper, we proposed two uncertainty reduction schemes. The first scheme is to find a number of solutions in a radius around the current solution and perform an average over the estimated growth rate of these solutions. We showed this method not only reduces the fluctuations due to the uncertainty but also improves the prediction accuracy. Also, the uncertainty may cause fluctuations in the fitness landscape that should be removed. We proposed a movement smoothing operator that reduces sudden changes in the fitness that are more likely due to noise. Another field of research is to study the fitness landscape properties of the optimization problem [49]–[51].

In the future, there could be any changes to the situation, for example, the discovery of vaccines. These changes would not change the applicability of the algorithm. If a vaccine is discovered, the proposed algorithm can still be used with vaccination being another policy added to the set of policies. Up to the point of the publication of this paper, not many countries have started vaccination and the ones who have implemented the policy, have not vaccinated enough of the population to clearly benefit from the effects. One line of future work can be the study of the effect of vaccination on the pandemic. There are many types of vaccines developed at the moment. These vaccines are different in their prices, cost of vaccination, effectiveness, etc. The proposed approach can be generalized to study the vaccination policies and to find the best policies in that regard.

At the time of the publication of this paper, a number of variations of the virus have evolved in some countries including the 20B/501Y.V1 variant (colloquially knows as UK variant) or 501Y.V2 variant (known as South Africa variant). Because these variants are known to have a higher infection rate, the behaviour of the pandemic relating to these variants will be different. Also, there are many factors that change the behaviour of the pandemic, including the level of herd immunity, the appearance of new variants, etc. The current version of the work can be improved in future work to consider these challenges. One approach could be to employ the algorithms that detect and manage concept drift. This remains for future work.

This pandemic has not been the first and will not be the last one that has affected humanity's life [52]. In the current patterns in the relationship between humans and wildlife, it is expected to have an increasing number of Zoonotic disease pandemics in the future [53]. The current pandemic may be over soon, but the need for approaches to tackle future pandemics remains. This paper should be considered as a stepping stone for the way AI approaches can be used to tackle pandemics.

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