Framework for Efficient Resource Planning in Pandemic Crisis

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***Abstract*—Pandemics have dramatic consequences, both taking human lives and ruining economy leading towards crisis worldwide. It has also been the case with COVID-19 pandemic since the beginning of this year. In this paper, we present a framework aiming efficient resource planning during the pandemic crisis, making use of modelling, simulation, predictions based on deep learning, linear optimization and blockchain. As a case study, we target the current COVID-19 pandemic. According to the achieved results, the proposed framework has not only huge potential in cost reduction, but also enables the proactive approach to tackle the pandemic which can save many lives as well.**

***Keywords*—blockchain, deep learning, coronavirus, COVID-19, linear optimization, modelling, simulation**

I. INTRODUCTION

In the first days of this year, a new infectious flu-alike disease *COVID-19* was discovered in China, after several strange pneumonia cases in Wuhan's Seafood Wholesale Market [1]. Behind this disease is *SARS-Cov-2* virus, also referred to as *2019-nCoV* or popularly *coronavirus*. However, its distinctive feature compared to other influenza viruses is actually the fact that even asymptomatic people might be potential sources of infection, which first caused a dramatic outbreak in China [2]. Moreover, long and varying incubation periods (normally from 2 to 14 days, in extreme cases up to 27 days) [3] and high death rate among elderly and people with chronic diseases makes the situation even more difficult to control and handle [1, 2].

After the outbreak in China, in just few weeks, the first cases were reported in other continents around the world, as well. In Europe, the first cases were recorded during the last week of January [4]. Later, towards the middle of February, the number of infected people in northern Italy has started to rise dramatically making it one of the world's worst-affected countries quite soon. The new disease quickly turned from Chinese outbreak to worldwide pandemic, having disastrous consequences - huge number of lost lives, but also catastrophic financial losses and stagnation of economy as well [2]. Towards the middle of March, COVID-19 hit most parts of Europe which led to different region-level government responses, such as limiting the citizens' movement, city lockdowns, closing country borders and social distancing [5]. As for now, there is no specific treatment for COVID-19 proven by clinical trials [6]. For all these reasons, the COVID-19 pandemic crisis was inevitable.

In pandemic, it is crucial to plan resources efficiently and timely, both human and material [7, 8, 9]. Moreover, the protection of health and the economy of a country are tightly connected [10]. On the other side, it was shown that simulation approach has many benefits in pandemic situations, leading to reduction of pandemic's consequences, especially at provincial and local level [9]. Therefore, in this paper, a software framework utilizing simulation is proposed targeting the efficient resource planning in context of current COVID-19 crisis.

In [8], simulation was used to tackle the past bird influenza pandemic. Recently, a simulation-based approach to prediction of COVID-19 spread in Iran was presented [11]. However, the work presented in our paper builds upon the approach approved in [12], combining energy consumption prediction and linear optimization for optimal blockchain-based energy trading within smart grids.

II. BACKGROUND AND RELATED WORKS

A. *Blockchain Technology*

The initial purpose of Bitcoin, the pioneer blockchain technology that emerged in 2009, was enabling the transfer of financial assets worldwide without involving intermediaries and transfer costs. Blockchain refers to a data structure (also called *ledger*) which represents an append-only sequence of blocks that hold the information about the executed transactions [13]. Moreover, the same term is also used for a distributed system that stores copies of the previously mentioned data structure within the peer-to-peer network of interconnected nodes. In this network, each node contains alphanumeric address, while both anonymity and transaction record transparency are kept at the same time. Apart from that, each block also includes a cryptographic hash of the previous block and timestamp to ensure that no modification or deletion is possible, once they are recorded within the ledger. The blockchain-enabled transaction represents the transfer of value and ownership of digital tokens between sender and receiver that is appended to the distributed ledger [13, 14]. Token can represent either tangible or intangible goods/assets. On the other side, *smart contract* refers to a protocol which has purpose to digitally facilitate, verify, or enforce the execution of a particular contract [14]. In blockchain technology, it refers to a software code that defines and executes transactions on the targeted platform, while the performed transactions are trackable, irreversible and do not involve third part.

In this paper, we consider the usage of Ethereum [1] blockchain in synergy with smart contracts that are written using a high-level object-oriented language Solidity[2]. The output of linear optimization process is leveraged to generate smart contracts for resource exchange between cities,

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[1] https://ethereum.org/

[2] https://solidity.readthedocs.io/en/v0.6.4/

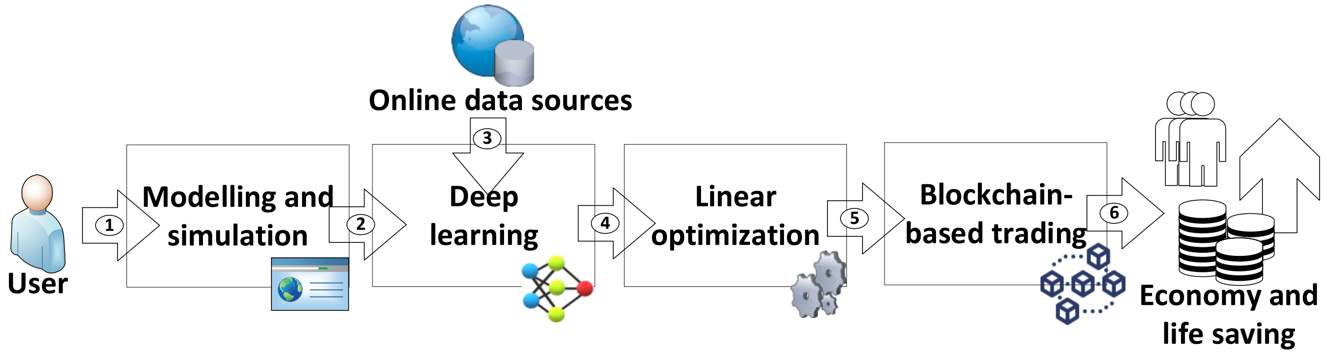

Fig. 1. Framework overview: 1-Model definition and simulation execution 2-City resource model 3-Aggregated and filtered public online data about new cases 4-Predictions based on past data 5-AMPL data file 6-Optimization output 7-Smart contract-based blockchain transactions

inspired by frameworks for energy trading relying on blockchain [12] and smart contract-driven music asset exchange approach from [15].

B. *Deep Learning*

Deep learning covers a family of various machine learning techniques and algorithms based on artificial neural networks. *Artificial Neural Network* (ANN) represents a collection of computational units interconnected via weighted links. These units are called *neurons* or *perceptrons*. Each of them has one or more weighted input connections, a transfer function that combines the recived inputs and an output connection to forward the result to connected units [16]. Three types of layers are identified in neural networks [16, 17]: 1) *input layer* - corresponds to the input variables 2) *hidden layer* – placed between input and output layers 3) *output layer* - generates the output variables. A *deep neural network* (DNN) is an artificial neural network (ANN) with multiple layers between the input and output layers [17].

For example, in [18], Markov model was used to predict the spread of COVID-19 in Germany. On the other side, in [19], an approach based on neural network was used for country-wise COVID-19 risk predictions, showing promising results. In our paper, deep learning approach is used for prediction of new cases and deaths on regional- or city- level, necessary for resource demand estimation used crucial parameters in the proposed linear optimization models. The prediction model is trained on publicly available online data about COVID-19 cases and deaths from previous periods on daily basis. TensorFlow[3] library for Python programming language was used for implementation of the prediction module. One of its advantages is the support for faster GPU-powered execution on CUDA-enabled hardware, which was used for energy consumption prediction in [15].

C. *Linear Optimization*

Linear optimization (also called *linear programming*) is a method which has a goal to achieve the best possible outcome (such as maximum profit or lowest possible cost), relying on a mathematical model, where the requirements are represented by linear relationships [20]. It refers to techniques for optimization of a linear *objective function*, subject to linear equality and inequality *constraints*. The vector of variables which are determined as a result of optimization process is called *decision variable*.

In this paper, linear programming is adopted to enable optimal resource planning and exchange between cities during COVID-19 pandemic crisis. The implementation is based on AMPL[4], an algebraic modeling language for mathematical programming. It enables writing linear programs using the expressions similar to traditional algebraic notation. However, AMPL is not responsible for solving optimization problems, but it rather provides interface to other programs responsible for that. In this paper, CPLEX[5] was used as a solver of optimization problems, while its implementation is based on simplex method [21].

III. IMPLEMENTATION OVERVIEW

A. *Framework Architecture*

In Fig. 1, an illustration of the proposed framework is shown.

First, user has to define models of cities and set parameters about the available resources for each city relying on a visual modelling environment tool run in web browser. A domain-specific notation is used for that purpose, while the modelling tool implementation is based on JavaScript, HTML and CSS on frontend and Node.js on backend.

Once the modelling is done, the simulation can be run within the tool. For that purpose, the city models are augmented with the data about expected resource demands based on the results of deep learning-based predictions. In order to enable making predictions, public data about number of new cases and deaths on daily basis from various online is collected, aggregated, filtered and prepared.

Furthermore, AMPL data file containing the city resource model augmented with predictions is transferred to linear optimization process with respect to pre-defined AMPL optimization models. Once the process of optimization is completed, its output which represents optimal resource exchange matrix is used for generation of Ethereum blockchain Solidity smart contracts. The aim of such contracts is to execute the proactive resource exchange transactions that would result saving both the city's economy and citizens' lives.

B. *Modelling Notation*

Domain-specific language is a programming language or notation specialized for solving problems from some domain of interest. In this paper, a domain-specific notation is used

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[3] https://www.tensorflow.org/

[4] https://ampl.com/

[5] https://www.ibm.com/analytics/cplex-optimizer

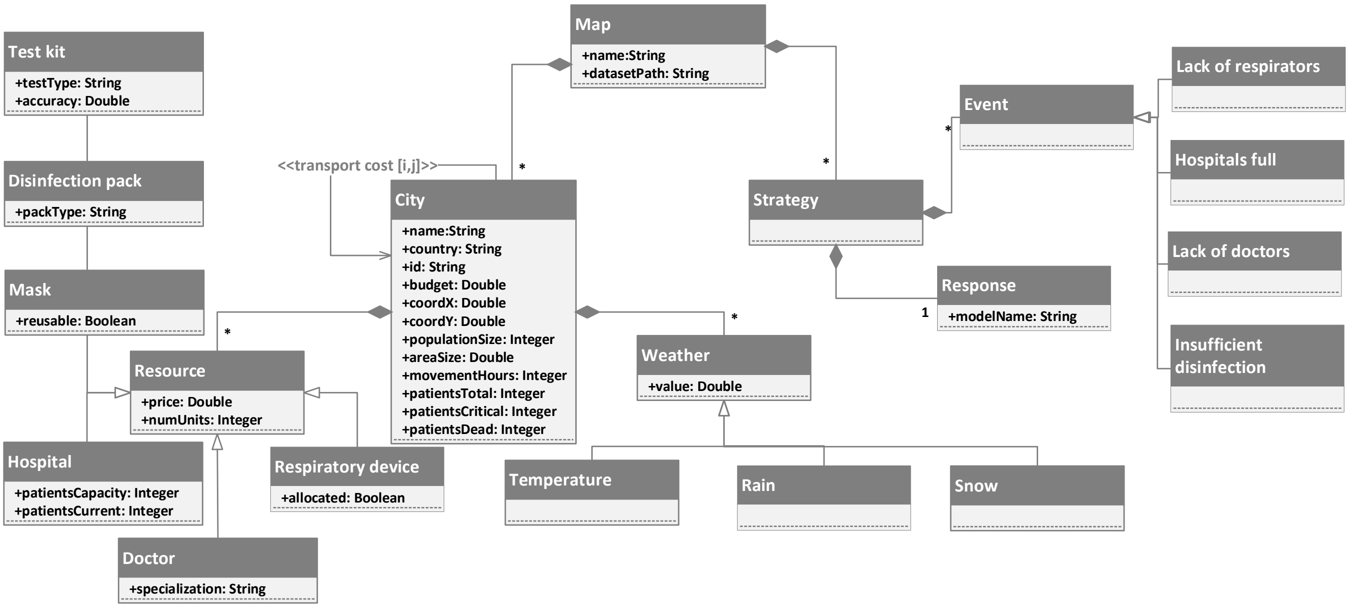


Fig. 2. City resource modelling notation metamodel represented as UML class diagram

for city resource modelling. In Fig. 2, a UML class diagram of the metamodel used for that purpose is shown.

The highest-level concept in modelling notation is *map*. It consists of a set of interconnected *cities* able to exchange resources during the pandemic crisis. The parameter describing the city connections is *transport cost*. In context of resource allocation, relevant parameters for cities are its area size, the total number of citizens, number of hours allowed for movement, total budget. Moreover, relevant parameters for pandemic situation are the total number of cases, number of critical cases and patients that died. There are several types of resources considered: *hospital buildings*, *doctors*, *disinfection products*, *respiratory devices*, *masks* and *test kits*. A common feature of all resources are their price and number of units available. Each hospital has a limited capacity of patients. At each moment, some of the places within the hospital are occupied. For COVID-19, respiratory equipment is crucial for saving lives in critical cases, therefore it is highlighted as one of the most important resources that are exchanged between the cities, apart from disinfection products and masks which can lead to reduction of infection spread [22]. Furthermore, it is possible to set the value of weather parameters, such as temperature, rain and snow, which can affect the people movement and, indirectly, the disease spread.

The implementation of modelling and simulation environment is built upon [12] and [23]. The tool offers two views: (a) map view and (b) city view. Map view gives a global illustration of the affected cities, while city view is available for each city from the map by double-clicking on it and is used to set resource parameters. In Fig. 3, a screenshot of the described tool is shown.

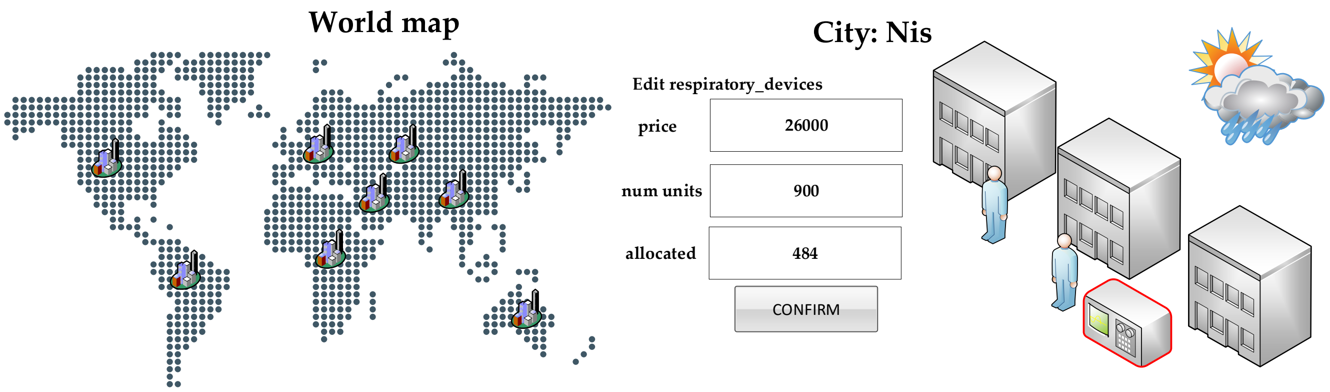
C. Simulation Mechanisms

It is possible to check whether the number of respiratory devices is sufficient by checking if it is greater or equal to the number of critical patients:

$$n\_critical\_patients \le n\_respiratory\_devices \tag{1}$$

Moreover, it can be checked whether the number of doctors available can handle the number of expected new cases based on estimation of how many patients each of them can treat:

$$\frac{n\_expected\_cases}{n\_patients\_daily\_per\_doctor} \le n\_doctors \tag{2}$$



Edit respiratory_devices

price: 26000

num units: 900

allocated: 484

Fig. 3. A screenshot of modelling and simulation tool: (a) map view (b) city view

It is also checked if there are enough free places in city hospitals to allocate the patients:

$$n\_expected\_cases \leq \sum_{i=1}^{n_h} hospital[i].free\_places \quad (3)$$

Furthermore, it is checked if the number of available test kits is above a given threshold that is 10 times the predicted number of cases:

$$0.1 \cdot n\_expected\_cases \leq n\_test\_kits \quad (4)$$

Finally, it is checked if the number of masks is at least 10 times greater than the city population size:

$$10 \cdot population\_size \leq \sum_{j=1}^{n_p} pharmacy[j].n\_masks \quad (5)$$

In case that one of the previous conditions is false, then the specific event is triggered in the simulation environment. After that, a user-defined resource exchange strategy based on optimization will be executed as response to that event:

$$if\,(event_i)\ then\ optimization(response_i.modelName) \quad (6)$$

D. Deep Learning-Based Spread Prediction

The aggregated online data is split into two disjoint sets – the training set (70%) and test set (30%). It consists of total eight variables, as it is shown in Table I.

TABLE I. DISEASE SPREAD PREDICTION DATASET

cid	***Density [p/km^2]***	***m_age [y]***	***Day [0..366]***	***T [°C]***	***mh [h]***	***New [p]***	***D [p]***

Cid is the identification number of the considered city. *Density* is number of persons per km^2 provides the information about population density within the area. *M_age* is the age that divides a population into two numerically equally sized sets, which might be of huge importance for prediction of death cases. Day is the ordinal number of a day in a year. *T* is the average daily temperature during the considered day which can have impact on the movement of citizens and disease spread, as proposed in [19]. Instead of temperature, other weather parameters might be leveraged, such as rainfall or snow. *Mh* represents the number of hours during the day when the citizens are allowed to go outside and may vary across countries and cities due to different government decisions. It is in range from 0 (total quarantine) to 24 hours. *New* refer to the number of new infected people identified within the area, as an average of 7 days which is approximately the average length of the incubation period [3]. *D* represents the number of people that died as a consequence of COVID-19 disease during the considered day. City id, density, age, day number, temperature and movement hours are treated as independent variables, while the number of new cases and deaths are dependent variables (predicted values). However, the information about population density, median age and movement hours are optional, but the predictions could also be made without them. The abbreviations of the measurement units have the following meaning in Table I: *p* - people, *y* - years, *p/km^2* – people per square kilometer, *h* -hours.

The data from public domain dataset about the new cases and deaths on national level worldwide was used from [24], together with national-level detailed data about COVID-19 in Serbia from [25].

E. Optimization Model

Several similar optimization models for different resource exchange strategies are implemented within the tool (respirators, test kits, masks, medical personnel, disinfection, and patients exchange), but one of them will be presented.

Let us consider a network of *nC* interconnected cities involved into resource trading, denoted as *C*. To each link between *c* travel cost *transport_cost[i,j]* is assigned. Each *city[i]* has predicted number of new cases *new_patients[i]* and available test kits *tests[i]*. Each *city[i]* has test kits of price *test_price[i]*. Furthermore, each *city[i]* has amount of budget *budget[i]* that is the maximum amount of money which can be spent.

To each connection between cities, a decision variable *x[i,j]* is assigned to indicate the amount of test kits that will be sent from *city[j]* to *city[i]*:

$$\begin{aligned} &x[i,j] \geq 0\ if\ trading\ between\ city_i\ and\ city_j\ will\ be\ perfromed, \\ &x[i,j] = 0\ \ otherwise \end{aligned} \quad (7)$$

Additionally, there are several resource exchange constraints.

First, the overall amount of available test kits after exchange is always equal or greater than the number of predicted cases multiplied by 10 in each of the considered cities:

$$tests[i] + \sum_{j \in C} x[i,j] - x[j,i] \geq 10 \cdot new\_patients[i],\ i \in C \quad (8)$$

Moreover, the total cost of test kit acquisition should not exceed the available budget of each city:

$$budget[i] \geq \sum_{j \in C} transport\_cost[j,i] + x[i,j]test\_price[j],\ i \in C \quad (9)$$

Finally, the objective function minimizes the overall sum of costs, considering both the travel cost and test kit:

$$minmize \sum_{i,j \in C} transport\_cost[j,i] + x[i,j]test\_price[j] \quad (10)$$

In Listing I, the AMPL code of the proposed optimization model for test kit exchange is given.

LISTING I. AMPL CODE FOR TEST KIT EXCHANGE MODEL

```
param nC;
set C:=1..nC;
param transport_cost {i in C, j in C};
param new_patients {i in C};
param tests {i in C};
param test_price {i in C};
param budget {i in C};

# variable declaration
var x {i in C, j in C} >= 0;

# objective function
minimize cost:
      sum{i in C, j in C} (transport_cost[j,i]+x[i,j]*test_price[j]);

subject to cover_estimated {i in C}:
      tests[i]+sum{j in C}(x[i,j]-x[j,i])>=10*new_patients[i];

subject to budget_threshold {i in C}:
      budget[i]>=sum{j in C}(transport_cost[j,i]+x[i,j]*test_price[j]);
```

F. Smart contract generation

The role of smart contract generation algorithm is to parametrize the smart contract templates for resource exchange. These contracts enable the execution of transactions according to the optimal resource allocation that was obtained as output of corresponding optimization processes. In Listing II, the smart contract generation is given in a form of pseudocode.

First, the optimization problem for the resource allocation strategy is solved for the corresponding model using as a response to event that occurs in simulation environment. The resource exchange matrix is created as a result of optimization process. After that, the matrix is traversed. For each resource exchange between *city[j]* to *city[i]*, the necessary parameters are retrieved and inserted to a smart contract template (similar to templates used in [12] and [15]): buyer and seller id, amount of resources that will be transferred, resource cost and transport cost. The amount of tokens is calculated as:

$$price = num\_resources[i, j] \cdot resource\_price[j] + transport\_cost[j, i] \tag{11}$$

LISTING II. PSEUDOCODE OF ALGORITHM FOR SMART CONTRACT GENERATION LEVERAGING OPTIMIZATION PROCESS OUTPUT

```
Input:  event in simulation environment
Output: A set of smart contracts
Steps:
 1. Perform optimization according to model response.modelName
 2. Store the resource exchange matrix obtained as result
 3. For i=1 to matrix.n
 4.     For j=1 to matrix.m
 5.         If(matrix[i,j]>0) then
 6.             Retrieve city[i] and city[j] identifiers
 7.             Retrieve resource cost offered by city[j]
 8.             Retrieve transport cost from city[j] to city[i]
 9.             Price:=transport_cost[j,i]+matrix[i,j]*resource_price[j]
10.             Parametrize_contract(city[i]_id, city[j]_id, price)
11.         Else
12.                 do nothing
13. end for each
14. end
```

IV. EVALUATION AND RESULTS

A laptop equipped with Intel i7 7700-HQ quad-core CPU running at 2.80GHz, GTX1050 GPU with 2GB VRAM, 16GB of DDR4 RAM and 1TB HDD was used for emulation of the proposed implementation. In Table II, the achieved results in test kit exchange scenario for different number of cities involved are given, considering the execution time for different processing steps (in seconds) and overall cost reduction (as percentage).

According to the results, the optimization processing time increases with the model size, but it does not exceed one second in the executed experiments. On the other side, the reduction of resource exchange costs and smart contract generation time depend from the specific problem instance itself and vary from case to case.

The relative error of predictions was around 30%, which is worse than the energy consumption prediction using a similar approach in [12]. This can be explained by the fact that amount of data about new COVID-19 cases in Serbia and worldwide was not so detailed during the process of writing this paper. Moreover, the cost reduction in all cases was also lower, leading to the conclusion that more accurate prediction could also impose greater cost reduction. On the other side, the contract generation time is faster than [12], as it does not rely on semantic triple store which involves many queries for retrieval of the desired information.

TABLE II. EVALUATION RESULTS

Size [nC]	***Prediction [s]***	***Optimization [s]***	***Contract gen. [s]***	***Cost red. [%]***
4	***0.31***	***0.019***	***1.31***	***27***
6	***0.33***	***0.028***	***3.34***	***41***
8	***0.49***	***0.081***	***1.12***	***33***

V. CONCLUSION AND FUTURE WORK

The proposed approach seems promising, providing the ability to timely allocate resources in a pandemic crisis situation and respond proactively. However, the proposed framework is still a work in progress and more data about new COVID-19 cases in Serbia and other countries will be used in future for more accurate predictions, potentially leading to greater cost reduction when it comes to resource planning during pandemic.

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