Ambulance Vehicle Routing under Pandemic with Fuzzy Cooperative Game via Smart Contracts

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Abstract: The pandemic caused by COVID-19 virus has posed a challenge for healthcare systems in many countries. One of the important tasks facing after a sick person detection is the timely patient’s transportation to a hospital. When making a decision on transportation to the hospital, it is necessary to account for many parameters, including beds space availability, availability of hospital staff and medicines required by the treatment protocol, diagnostic equipment on ambulance team, the distance to the hospital, ambulance vehicle locations, as well as hospital and ambulance staff psychophysical state, and patient’s reaction to hospitalization. Some of them can be gathered through smart city sources, like city databases or operational systems, but most of them require access to medical services. It is proposed to consider hospitals as participants of a cooperative game, whose overall goal is to ensure the maximum of cured patients. To describe the psychophysical state of the personnel, as well as to ensure greater variability of the resulting solution, the game parameters are proposed to be set using fuzzy sets and fuzzy logic. To implement the game rules, it is proposed to use smart contracts in blockchain technology. The blockchain could also be used to provide access to data from medical services, store and distribute the current state of hospitals, and save processing results for later analysis and model refinement.

1 INTRODUCTION

Coronavirus pandemic has proven to be a major challenge for healthcare systems in many countries. One of the problems was the patient’s timely hospitalization, given the limited number of ambulance vehicles and bed space in hospitals.

When discussing the problem sources and possible solutions, a large number of factors must be considered (Patel et al., 2020); at that, four large groups can be distinguished, associated with the main actors: hospital, patient, ambulance, a dispatcher (distribution center). Each of them, due to the increased load, must constantly monitor the current situation and promptly form a solution suitable for all participants in the process (see Fig. 1) (Xiong et al., 2020). The complexity of the problem of patient distribution is the stochasticity of their admission and a high rate of change in the operational situation. High load causes an increased impact on the psychological and emotional state of staff and patients. This leads to distress increase and errors’ number increase during decision making that can reduce the care speed and quality (Patel et al., 2020; Xiong et al., 2020).

The paper proposes considering a narrower problem associated with the patients’ hospitalization under a pandemic. A methodology for using information technologies to support decision-making for ambulance vehicle routing during hospitalization is proposed. It is based on the division of the problem into two tasks: 1) making a decision on hospitalization with the selection of an ambulance vehicle and 2) the selection of a hospital to which the patient must be transported with the selected vehicle. For each task, several parameters are estimated that describe both the quantitative characteristics of the task, such as the availability of vacant places (beds) in hospitals, the average transportation time, the number of ambulance vehicles, the cost of treatment, and the qualitative parameters associated with the psychoemotional load on patients, dispatchers, and medical staff.

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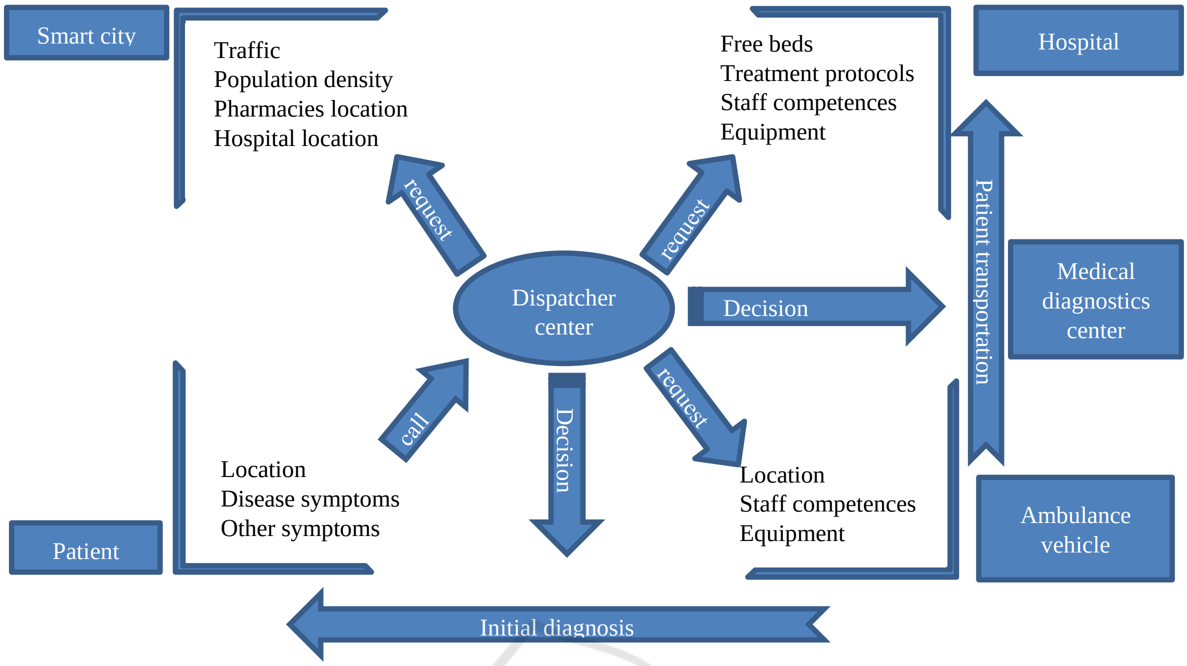

Figure 1: Decision making on ambulance vehicle routing for patient treatment.

The choice of a hospital is carried out through the formation of a cooperative game in which hospitals are participants. The cooperative game characteristic function estimates benefit of cooperation as the number of patients cured under the constraints imposed by each participant under current conditions, like, the supply of medicines, the availability of equipment, the probability of successful treatment and psycological state of medical staff. To take into account the probabilistic characteristics and psychological state of medical personnel, it is proposed to use fuzzy logic and fuzzy sets.

To quickly track the current situation in this work, it is proposed to use blockchain and smart contracts. Blockchain capabilities allow to save patient medical records and permit access to them only by authorized staff. It is also possible to store the current state according to the main parameters that can describe the current situation. Smart contracts in the form of decentralized applications can be used to compute the outcome of the coalition game and support decision-making during a hospitalization.

The paper is structured as follows. Section 2 describes the current state of research on the use of information technology to support decision-making in healthcare. Section 3 describes the decision-making methodology for hospitalization under a pandemic. Section 4 contains a description of describes the hospitalization process as a fuzzy cooperative game and the parameters that should be taken into account when making an appropriate decision. The work conclusion provides general conclusions and directions for further work.

2 RELATED WORK

Currently, the application of information technologies to healthcare is an active and promising research area. The range of their applications is quite wide: from storing medical records, containing all parameters of a patient and her/his health history are saved (Dalianis, 2018), to the use of artificial intelligence for identifying diagnoses and searching for medicines for a specific disease of a particular patient (Topol, 2019; Yu et al., 2018).

It should also be noted that the use of information technology in healthcare is focused on the processing of information that is usually classified as personal data and medical secrecy. This requires corresponding levels of security for the subsystems responsible for processing, storing, transferring, and providing access to the information. In the event of an epidemic, however, it is necessary to provide online access to this information (Raskar et al., 2020). The recent advanced studies suggest an application of the distributed ledger technology based on the blockchain concept to solve this problem, as well as smart contracts technology that expands its capabilities. The research efforts are focused on developing scalable systems for collecting readings from sensors that monitor the patient's condition (Jamil et al., 2020; Satamraju & Malarkodi, 2020), creating distributed systems for accessing patient data during routine examinations, and making diagnoses in case of illness (Satamraju & Malarkodi, 2020; S. Wang et al., 2018; Z. Wang et al., 2020).

It is also worth noting existing interdisciplinary research combining the technologies of the Internet of Things, supply chains, and the distributed ledger in healthcare. Thus, in (Islam & Young Shin, 2020), a system is proposed that collects data from patients using unmanned aerial vehicles furnished with special equipment. The collected data are encrypted and moved to the nearest server, where they are decrypted and put onto a medical record, access to which is organized by calling functions of smart contracts implemented using the Solidity language in the Ethereum blockchain platform. This scheme provides remote diagnostics using professional equipment, with full protection of all patient's personal data from the measurement moment to the medical doctor submission.

Another study suggests using blockchain to control the vaccine supply chain (Yong et al., 2020). Within the framework of the developed system, the control of the stages from the creation of a vaccine to its application by a doctor is provided. This enables tracking the distribution process, covering the population with the vaccine, and is compliant with the conditions and terms of the vaccine transportation and storage, which allows for avoiding negative consequences caused by damage of the vaccine due to any violation at any stage of delivery. Additionally, the system includes a recommendation module based on a neural network of the LSTM (long short-term memory) model for assessing the vaccine demand based on the results of the previous vaccination.

3 DECISION SUPPORT ON AMBULANCE VEHICLE ROUTING UNDER A PANDEMIC

3.1 Common Requirements

Since the resources used to overcome the consequences of epidemics are limited, it is assumed that their distribution should be directed towards solutions that are most effective in the current situation. Agents (participants) form coalitions to use these resources in which the competencies of each agent correspond best to the particular problem being solved. The contribution of each member of the coalition is estimating as a payoff for task solving based on the benefit that coalition will gain after successful task solving. For example, in the case of hospitalization task the benefit will be the ratio of cured patients to the number of deaths. It is proposed to evaluate the effectiveness of socially-oriented decisions as to the ratio of funds spent on treatment to potential losses from deaths, while it should be borne in mind that losses significantly exceed any spent funds.

The gain of the coalition in this case can be estimated as the difference between the potential losses and the funds spent. To motivate agents when working in a coalition, the entire total payoff (or part of it) can be distributed among them. This model allows for applying fuzzy cooperative games to form a coalition and distribute the payoff between the members of the coalition. Fuzziness in this problem allows for operating with fuzzy values of efficiency and gain, which provides flexibility and variability of the solutions obtained, as well as to account for retrospective estimates of the level of uncertainty distress among participants, including those arising under the influence of competing for external regulators of behavior.

3.2 Social and Psychological Characteristics for Decision Support

It is proposed to use a mathematical formalism to describe human behavior. For example, in (Kleiner et al., 2018), a model of psychological factors of economic behavior is considered, that includes the systemic structure of an agent (person), presented in the work as a set of four interacting subsystems: intentional (agent's intentions), anticipatory (agent's expectations), cognitive (agent's perception of the surrounding world) and functional (agent's behavior). Analysis and compilation of behavior models are also used to predict human actions, for example, in tourism (Gretzel et al., 2015) and marketing (Stalidis et al., 2015). In this case, the description can be based on various formalizations, for instance, first-order logic, description logic, classical algebraic formulas, consistent with the proposed methodology.

In studies conducted in the context of the 2020 pandemic, it is noted that the incompleteness of a threatening situation produces a major effect on people, and the cumulative nature of the stress effect is recorded (Xiong et al., 2020). Unfavorable background factors for all participants in the decision-making process are anxiety, fear of infection, forced isolation from family members (Shah et al., 2020), anxiety, and depressive states increase (Montemurro, 2020). The behavior of patients is influenced by the stress, fear, depression caused by the disease itself and its severity; and by the stress associated, according to foreign scientists, with a "health crisis" (Garfin et al., 2020), which is largely due to the dissemination of threatening, emotional, and sometimes redundant information about an invisible threat, which in isolation leads to the constant appeal of people to its sources, doubts that in these conditions one can count on a full and high-quality medical service. Lack of protective equipment, problems with adequate treatment, as well as a purely human factor - fatigue, tension, anxiety, and professional burnout of medical personnel (Li et al., 2020; Mo et al., 2020; Montemurro, 2020), induce negative emotional states in the hospitalized, attempts to influence the decisions of medical personnel.

Decision-making by medical workers, management personnel, operational workers is carried out against a background of fatigue, stress, and distress. Uncertainty distress has become a key factor in the impact on medical staff in COVID-19 (Freeston et al., 2020). The uncertainty of the diagnosis and prognosis of treatment is associated with the lack of reliable and complete information about the disease and the forms of its manifestation, treatment methods, considering the individual characteristics of patients. These features of the diagnosis are the characteristic of the current situation of a pandemic, in which the diagnosis is not always defined timely, it is formulated vaguely and unclearly, the disease manifests itself variably, and a high variety of symptoms is demonstrated.

As several studies have shown (Buheji et al., 2020), stress occurs when a person is sensitive to the perception of environmental stimuli, while her/his resources are aimed at correcting the impact of the environment or changing it are insufficient. In the context of the ongoing pandemic, methods are being developed to express diagnostics of anxiety, states of uncertainty in large samples, and attempts are being made to assess the emotional state of individual social groups or society as a whole (Ahorsu et al., 2020; Pakpour & Griffiths, 2020).

Formalization of stress indicators requires high variability with the possibility of states' fuzzy description. The most effective tool in this case is fuzzy sets. Within the framework of the methodology, fuzzy sets can be used together with the mathematical apparatus of fuzzy logic and fuzzy cooperative games, which provide the formalization of the patient and doctor's state and also form constraints for the optimization problem being solved.

The use of fuzzy logic and fuzzy cooperative games in describing the interaction of coalition participants is a relatively new approach that has shown, however, its effectiveness in problems of supply chain configuration (Sheremetov, 2009) and coalition formation (Mohebbi & Li, 2015). From the medical point of view, the apparatus of fuzzy logic and cooperative games can be used to assess the effectiveness of hospitals (Omrani et al., 2018). The effectiveness in this work is assessed by many parameters, including the number and quality of staff (doctors, nurses, support staff), the number of beds, the number of operations, costs of treatment and maintenance, etc. The mechanism of coalition games was used after the division of the country (in this study, Iran) into separate regions according to economic and demographic parameters, and the assumption that each hospital works in cooperation with other hospitals in the region. This allowed to calculate the total gain for the region and track the contribution of each hospital to the total gain.

4 FUZZY COOPERATIVE GAME USAGE FOR AMBULANCE VEHICLE ROUTING

To formulate the ambulance vehicle routing problem, an analysis of open sources and official documents of the Russian Ministry of Health was carried out.

According to the model, two related tasks can be distinguished that must be solved during the hospitalization process.

4.1 Initial Diagnosis

The first task is to determine the need for hospitalization and the selection of the ambulance vehicle from the vehicle pool (Fig. 2).

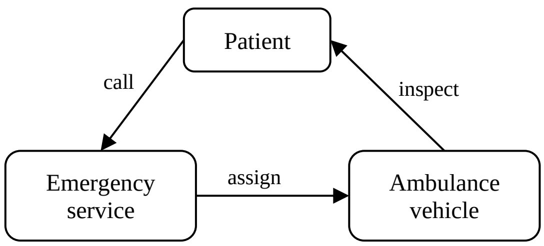

Figure 2: Initial call dispatching problem.

Upon receipt of a call from a patient, a short survey is conducted to estimate the probability of a particular disease. The survey, beside questions to identify the main symptoms, may contain questions about concomitant diseases, gender, age, and recent contacts. Additionally, the location of the patient and his/her medical insurance is being specified.

After collecting the information, the dispatcher service must estimate the need for hospitalization (at least half of the symptoms of the disease has to be confirmed). Then, based on the current demand and availability, an ambulance is selected, which has the necessary equipment and medicines for preliminary examination and potential hospitalization.

As part of the developed methodology, dispatchers are offered a decision support system evaluating the need for hospitalization and selecting an appropriate ambulance vehicle. The set of parameters to be used for decision support includes:

Global Parameters:

- Healthcare system priorities;
- General epidemiological situation.

Information Gathered from the Dispatcher:

- Number of calls for a day;
- The average severity of patients who require hospitalization;
- The average distance from the patient's location to the hospital (ambulance service radius);
- Vacant beds in hospitals;
- Average queue time for ambulance appointments in case of hospitalization.

Information from Ambulance Cars:

- Location;
- Staff quality (Average decision time, number of errors (the patient returns to the place of residence));
- Ambulance equipment (medical drugs, tools, tests);
- Staff working time (fatigue level).

The problem of choosing an ambulance for hospitalization is proposed to be formulated as a choice problem. Moreover, if an ambulance is already with the patient, then it is only necessary to solve the problem of choosing a hospital. Otherwise, after choosing a hospital, it is necessary to be guided by the parameters listed above, as constraints in the selection problem.

4.2 Hospital Selection

The second task is to choose the hospital, the patient needs to be transported to (Fig. 3).

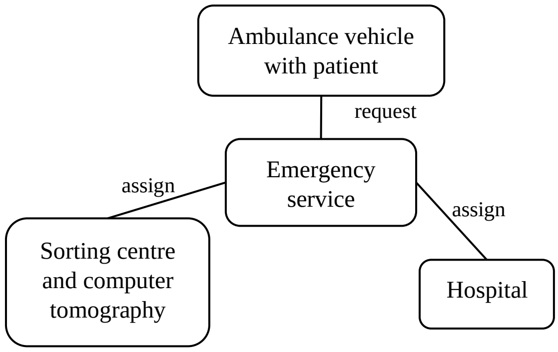

Figure 3: Process of patient transportation to hospital.

After an ambulance is assigned to a patient, the ambulance staff is responsible for the state of the patient. They need to conduct an initial examination using their equipment and decide whether the patient needs an urgent hospitalization or transportation to a sorting center or for additional testing. For example, in the case of COVID-19, computer tomography of the lungs may be necessary to confirm the diagnosis and the need for hospitalization.

When deciding on hospitalization, it is necessary to choose a hospital that has vacant beds and all the necessary equipment to treat the patient with the given severity of the disease. For this purpose, it is also necessary to contact the dispatcher, who, based on the assessment of the current situation, decides on the place of additional examination or hospitalization.

When solving this problem, it is also necessary to consider many parameters, including:

Patient and Ambulance Parameters:

- Patient condition (Condition description sheet (20 parameters and general assessment), comorbidities, age);
- Location.

Dispatcher Parameters:

- Healthcare system priorities;
- Road traffic;
- Sorting and laboratory parameters;
- Service time for one patient;
- Service queue;
- Resources (tests, disinfectant materials);
- Free seats;
- Cleaning and disinfection time after service.

Hospital Parameters

- Service time for one patient;
- Queue length;
- Bed amount;
- Available treatment protocols and scripts;
- Available resources (medicines, equipment);

- Bed quality (availability of additional functions and/or equipment to ensure comfort and relief of the patient's condition);
- Staff qualification and competences.

This problem is proposed to be formulated using the formalism of a cooperative game. The hospitals in the game are the players among whom it is needed to assign patients. Also, the players are diagnostic centers and distribution centers. A coalition can be formed between hospitals (in the absence of full compliance with the treatment protocol), between hospitals, and diagnostic centers.

Let us introduce a formalization of the coalition game for choosing a coalition of hospitals. Each of the players $i \in N$ aims at providing patient care P (transferring him from the "sick" state to the "healthy" state), guided by the treatment protocol (strategy) S_i using own resourcesR_i. Hospitals can form coalitions to pool their resources to achieve a goal within existing strategies. When solving a coalition game, a set of coalition participants is formed, to which the patient is assigned to (1). In this case, the coalitions of one participant are possible if he has the necessary resources to achieve the goal.

$$f_i\left(Y, s_j^K, s_i^{N\backslash K}\right) > f_i\left(Y, s_j^K | s_{iq \in S^{N\backslash K}}, s^{N\backslash K}\right) \quad (1)$$

Where K is the coalition, f_i is a characteristic function that is calculated based on the the current parameters Y of patient $p \in P$ and player q of the coalition K, $s^{N\backslash K}$ is the strategy of the player of the coalition K. It is proposed to formalize stress levels, the psychological and physical state of hospital staff and patients through linguistic variables such as $< f, L, X >$, where f is the name of the variable, L is the set of values and their membership functions, X is the carrier of the fuzzy set.

5 SMART CONTRACTS UTILIZATION

When organizing the exchange of information within the framework of the methodology, it is proposed to use the capabilities of a distributed digital ledger. The rationale for this decision is the need to provide trusted access for various services to electronic health records to speed up the exchange of information about the patient's condition, to save the history of changes in the state. Using the smart contract mechanism, a distributed ledger can be configured to control access to electronic health records.

Smart contracts are used as a distributed application. The contracts implement the logic of solving the coalition game. They take the current state of the players as input and form a decision that is stored in the distributed ledger. According to the decision received, the appointment of the hospital is carried out and, after approval by the dispatcher, the process of transporting the patient to the hospital is started.

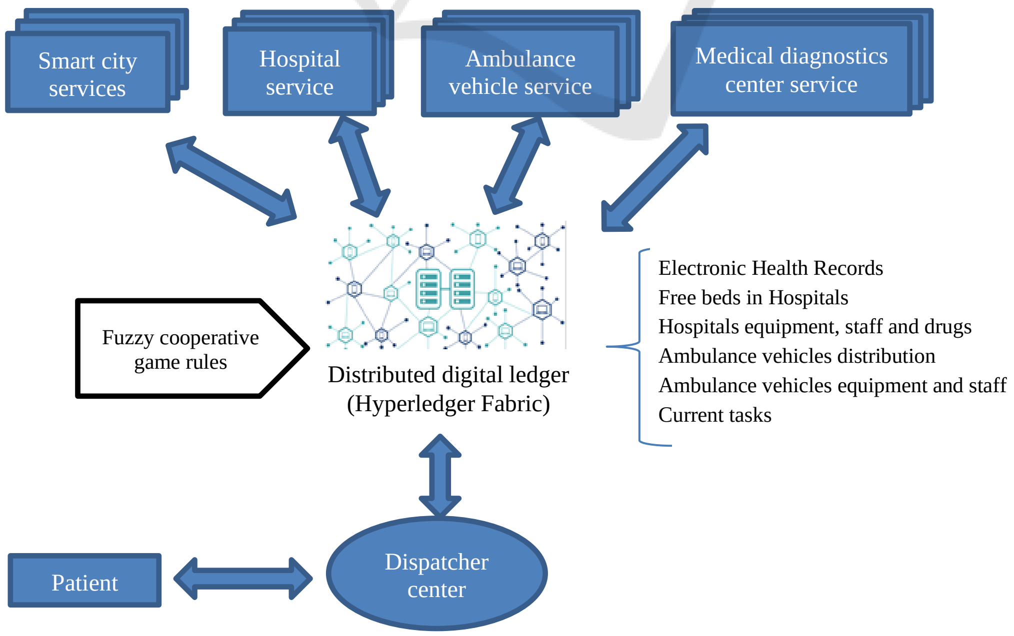

Figure 4: Decision making through with fuzzy cooperative game via smart contracts.

The system for decision making on ambulance vehicle routing is presented in Figure 4. Sources of information about the current state of the system are represented by services in the information space. Each service is associated with a distributed ledger and can transfer data through blocks in the ledger. When requested by a patient, the dispatch center can quickly receive current information and recommendations on where to transport the patient. The recommendation is formed by calling a smart contract containing the rules of a cooperative game. By placing contracts in the digital ledger, all blocks can be accessed from a smart contract, which allows to quickly get the current state of the system and form a coalition composition that corresponds to maximum benefit (to cure a sick person).

The Hyperledger Fabric platform is used to form a distributed ledger (Androulaki et al., 2018). Its choice is due to the possibility of forming separate chains of blocks corresponding to hospitals or electronic patient records. Using built-in capabilities for the implementation of smart contracts, access control to medical records can be controlled. Complex contracts can also be implemented to calculate the outcome of a coalition game.

The example of smart contract for core calculation is presented at listing 1.

Listing 1: Example of a chaincode for coalition calculation.

```
var hospitals []Hospital // Hospital
list
var patient Patient // Patients list
var K, K_prev        // coalitions
func coalitionCalc(stub
shim.ChaincodeStubInterface, args
[]string) (string, error) {
hospitals[i], patient = args[i],
args[j]
for h in hospitals {
  K = f(patient, h)
  if K > K_prev
    K = K_prev
  }
}
stub.PutState(K)
}
```

Preliminary experiments had shown that information exchange between coalition participants through smart contracts requires about 20 ms for each exchange transaction that includes information transfer, store in digital ledger and sharing between all coalition participants. The test stand had the following configuration: CPU Intel i7 7700k, RAM 16 Gb, SSD M2, 240 Gb.

6 CONCLUSIONS

The work shows the formalization of the transportation process using a fuzzy cooperative game problem that takes into account the main parameters of the hospitals and patients as the values of the objective function, and the limitations of the health care system as the limitations of the function. The main impact on the proposed methodology is concentrated on taking into account the economic effect and human behavior with an increase in the level of stress in the methodology. All parameters are formalized with the fuzzy sets and their consideration in the objective function is done using the fuzzy logic.

For the exchange of data on the current situation, the use of a digital distributed ledger is proposed. The decision of the target function and decision making, in this case, can be implemented in the form of smart contracts in the ledger. This approach ensures the consistency and immutability of data in the decision-making process and the accumulation of statistics for subsequent objective analysis of the pandemic.

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