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Introduction to the special issue on the role of operational research in future epidemics/ pandemics

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1. Introduction

In 1918–19, the Spanish flu (known as the 1918 influenza pandemic) infected around 500 million people worldwide, which was one-third of the world’s population at the time. At least 50 million people died, including about 675,000 people in the United States. One century after the 1918 influenza, COVID-19 was identified in December 2019 in Wuhan, China. On 11 March 2020, the World Health Organization (WHO) declared the outbreak a pandemic. Then, many people, particularly scientists and policy makers, thought we would experience another catastrophe like 1918 influenza? Can we anticipate the trajectory of the outbreak? Are there any ways to mitigate its impact? Once this disaster is over, do we have any comprehensive plan to guarantee we can prevent a similar disaster again? How can models help us minimize economic impact and relaunch the economy in such circumstances?

1.1. The origin of this special issue

In such an exceptional situation, many scientists were trying to contribute to the global effort to fight the pandemic in various disciplines such as healthcare, pharmaceutical, social, economic, operations, etc. As Operations Research (OR) researchers, we also thought about how OR techniques could contribute? Consequently, we planned to set up a special issue (SI) in the European Journal of Operational Research (EJOR), as one of the flagship OR journals and persuade OR, Management Science (MS), and Operations Management (OM) experts from various backgrounds such as healthcare, industrial engineering, and computer science to explore various research problems that can mitigate the adverse impacts of the pandemic.

Over recent decades, OR techniques have proven their ability to make appropriate strategic, tactical, and operational decisions. Any public, private, service, and manufacturing sector can use OR techniques to optimize its performance. While OR has already made a significant contribution to disaster management and humanitarian operations (Van Wassenhove 2006; Altay & Green III 2006; Gupta et al. 2022), it seems the nature of epidemic outbreaks and pandemics are significantly different from other disasters in terms of their dynamic nature, global scale and length. This SI aims to publish rigorous research based on the application of OR to epidemics and pandemics.

At the time of the SI proposal on April 9, 2020, over 1.6 million people had been infected and approximately 95,000 people had died. In less than a year, some vaccines were introduced to the world. Initial mass vaccinations started in December 2020. However, at the time of the writing of this editorial (end of June 2022), according to https://www.worldometers.info/coronavirus/, 548,765,419 cases were reported and 6,350,545 people died due to the pandemic. Of course, such data are not flawless because
some people were infected more than once, many infections were not identified/recorded, some people who died had a background disease, and some nations did not have a reliable data collection and reporting system. What is evident is that COVID-19 and other recent disease outbreaks, including SARS between 2002 and 2004, H1N1 in 2009, and Ebola between 2014 and 2016 proved that our societies are not as resilient as perceived and are not prepared for such disasters.

1.2. The accepted papers

Following the EJOR guidelines, we considered high-quality, original papers that contribute to the methodology of operational research (OR) and the practice of decision making but focus on epidemics and pandemics as the main SI topic. We urged academics to develop innovative OR-based ideas without limitation in areas and scope (e.g., social, logistics, resource allocation, supply chain, healthcare, agriculture, retail, energy, medicine, technology, and epidemiology) to prescribe impactful insights to academics, practitioners and policymakers.

The SI was seeking Innovative Applications of OR with solid methodological advancements. Case studies were especially welcomed, provided they are not simple case studies or direct applications of known methodologies and techniques to known problems. Any traditional, modern, exact, or heuristic technique as the development or extension of OR methodology fit for epidemic/pandemic contexts was also considered.

We received 112 papers submitted to “the Feature Cluster”. Of these, 23 were accepted, and 89 were rejected (79.5% rejection rate). In the following sections, we categorize and detail the accepted papers.

2. Transmission, propagation and forecasting

Global sensitivity analysis: Lu and Borgonovo (2022) study compartmental epidemiological modeling in infectious diseases. They propose a goal-oriented susceptible-infectious-recovered (SIR) model recently used in the context of the COVID-19 pandemic but focus on three sensitivity settings: (i) factor prioritization that prioritizes the key uncertainty drivers, (ii) trend analysis showing how the model output behaves as a function of one or more inputs, and (iii) interaction quantification that determines the most critical interactions in the model and their types (i.e., synergic –positive– or antagonistic –negative–). Then, probabilistic sensitivity techniques and machine learning tools are developed to solve the problem. Finally, they fitted the model to data corresponding to the four-time series: Italy, Spain, Germany, and the U.S.A., each including 56 days. The results show that quarantine rate and intervention time are the key uncertainty drivers, having opposite effects on the number of total infected individuals and are involved in the most relevant interactions. Also, the intervention time is the most important input in Italy. Still, it is less critical in the U.S.A., where intervention policies were state-based and lacked a centralized intervention date for a national lockdown. According to uncertainty quantification analysis, the intervention-related parameters in the model create more variability than the epidemiological parameters. Moreover, based on the trend analysis, a delay in implementing intervention measures can notably increase the expected total number of infected individuals. Also, according to interaction quantification analysis, a strong interaction between intervention time and quarantine rate for Italy and between quarantine and infection rates for the U.S.A.

COVID-19 Mortality Forecasting: Taylor and Taylor (2022) study mortality forecasting during the COVID-19 pandemic. They present an empirical comparison between combination methods for distributional forecasts of cumulative mortality. Furthermore, they forecast a probability distribution rather than just a single-point forecast. So, in the proposed model, interval forecasting techniques are used to support decision-making and provide situational awareness. In addition to the available forecasting methods such as simple average, median, and trimming methods, several proposed new weighted combination methods are also analyzed.

The authors study the weekly forecasting of cumulative mortality at the national and state level in the U.S.A. based on publicly available data from the COVID-19 Forecast Hub across the 40 weeks. A notable characteristic of this dataset is that the availability of forecasts from the participating forecasting teams varies greatly across the duration of the dataset. This situation has led researchers to focus on combination methods that do not rely on the historical accuracy of the individual forecasters. The results show that, although the median of all methods was very useful for the early weeks of the pandemic. The simple average was preferable after that. As a history of forecast accuracy accumulates, the best results can be produced by a weighted combination method that uses weights that are inversely proportional to the historical accuracy of the individual forecasting teams.

Identification of carriers and infection rate: Tsiiligiani, Tsiiligiani & Tsiiliganni (2022) study the identification of carriers and the infection rate of COVID-19. They present an inventory model to analyze the real-time identification of carriers. In the proposed inventory model, inventory in a warehouse is paralleled with people who carry the disease (CD). The warehouse is charged from the population side by new infected carriers with an infection rate (IR). The infection rate is modeled after supply in classical inventory theory. Then, this warehouse has two output flows (i) carriers who enter to health care unit (HCU) or intensive care unit (ICU), and (ii) the early exodus who exit from this inventory either by self-curing or death.

Two random and unobservable variables, i.e., (1) CD is the number of all carriers conveying the SARS-CoV-2, and (2) IR is considered the main target of restrictive measures (e.g., social distancing). Both variables affect the spread of the disease, the arrival rate to health care units (HCUs), and the number of victims. The mitigating actions and policies considered by the government to control the COVID19 are the intensity of social distancing, mobility measures, and level of immunity (as reflected by vaccination).

They develop a Markov chain Monte Carlo (MCMC) model to solve this queuing system where IR is considered the arrival rate. Four case studies are presented for Greece, China, Italy, and the U.S.A. According to the results, the design of policies restricts COVID-19 and also reduces the load of entering to HCU. Also, the policies mitigate economic contraction. Furthermore, based on asymptotic laws, the proposed method leads to satisfactory results according to the least-squares of the estimation error (LSE). Also, the model provides a satisfactory estimation with a lag of one week.

Local virus outbreaks: Chang & Kaplan (2022) study the modeling of local coronavirus outbreaks by developing a renewal equation approach. The model emphasizes how the incidence of infections in the past drives the current rate of new infections. The model is based on two types of infected people: (i) a person who has been infected early in an outbreak for a long time, or (ii) a person surrounded by individuals susceptible to infection who transmit disease with a Poisson rate. In addition, the research analyzes the effectiveness of isolation policies to separate infectious from susceptible individuals.

The researchers propose a model which integrates early transmission dynamics with the renewal epidemic model. The model considers the early phase of an outbreak corresponding to exponential growth in the incidence of new infections. Accordingly, a random variable- as a forward generation lag- is used to relate
the current incidence of infection to its past value. Thus, to handle the pivotal role of the forward generation lag, the effective reproduction number is estimated using epidemic indicators (such as the number of cases, hospitalizations, and deaths with the unobservable incidence of infection). Also, they analyze the effect of the herd immunity threshold in reducing transmitted infections. According to the results, the final size of unmitigated “worst-case” outbreaks and the depletion of susceptible people (whether by infection or vaccination) are necessary to achieve herd immunity. Also, the model shows that the testing frequency is required to ensure that repeat asymptomatic screening reduces the spread of infection to manageable levels.

3. Non-pharmaceutical intervention

Government's intervention strategies: Eryarsoy, Shahnazari & Tanrisever (2022) study the government’s intervention strategies during a pandemic. The term intervention refers to the strategies defined by the government to reduce the pressure on the healthcare system. These include self-isolation, social distancing, contact restrictions, school closures, business closures, quarantining the most vulnerable, banning public events, and national lockdown. In addition, they focus on elucidating the relationship between non-pharmaceutical interventions and key problem parameters, including (i) disease severity, (ii) economic severity of measures, and (iii) social and political concerns of the decision-maker. They quantify the costs and the level of containment efforts associated with such interventions. Additionally, they consider the monetary equivalent of intervention cost and several lost lives due to the lack of hospital ICU capacity as decision variables. Thus, the proposed multi-period intervention problem with causalities (MIPC) minimizes the total lost lives by controlling intervention levels. To solve the model, an effective hybrid variable neighborhood search algorithm to solve real-sized problem instances is used. The authors present two sets of experiments to analyze the model's applicability. The first one is adapted to the proposed MIPC model. For the second experiment, MIPC uses restrictions to address the containment problem’s social and political aspects. Each set of experiments is conducted for 91 weeks of planning horizon, or about 1.5 years.

The research shows that healthcare overcapacity will emerge when anticipated economic consequences are high. When the projected economic costs of the pandemic are large and the illness severity is low, however, a no-intervention strategy may be preferable. Also, the impact of social and political concerns on total containment effort (total spending) is not trivial. Except when the economic severity of the disease is high, social and political concerns always result in increased containment efforts. When the economic severity is high, depending on the levels of disease severity, these concerns may result in reduced containment efforts.

Economic Impact of Social Distancing: Chen, Pun & Wong (2022) study the effect of social distancing in mitigating COVID-19 from the economic and healthcare perspectives. They propose an epidemic control framework that policymakers can use as a data-driven decision support tool. The mobility indices are considered independent variables. These cover changes in mobility relative to the baseline (median values of the index) in the areas of retail recreation (RR), grocery & pharmacy (GP), parks (PA), transit stations (TS), workplaces (WP), and residential (RE).

The framework uses daily COVID-19 pandemic and economic situation historical data such as financial market instability (as a measure of the pandemic’s effect on the economy), mobility indices, and the number of infections, recoveries, and deaths. The proposed multi-objective framework minimizes the aggregated risks of disease transmission and economic volatility. Thus, the model presents a non-dominated frontier that explains the tradeoff between public health and market stability risks.

The authors suggest a stochastic susceptible–infected–recovered–deceased (SIRD) model that uses the concept of an efficient social distancing policy (ESDP), defined as a community mobility target. First, the researchers implement the TensorFlow platform’s deep learning technique to solve the problem. Then, they apply the proposed framework to the U.S.A. data and empirically examine the efficiency of the social distancing policies. Finally, Google’s community mobility data is exploited to assess the impact of social distancing policies on peoples’ movements in each geographic region.

According to the result of the U.S.A. case, the fittings of the stochastic SIRD model improve significantly with the inclusion of mobility data. Also, during the pandemic crisis, the power of the mobility indices in explaining market index responses is meaningfully high. It means that the stock market is more sensitive to pandemic situations and community mobility patterns during the pandemic.

Contiguous policy zones: Baghersad, Emadikhiav, Huang & Behara (2022) study the contiguous policy zones for the COVID-19 pandemic. They consider a geographic region, e.g., a country or community, divided into several mutually exclusive and collectively exhaustive spatial units (SUs) such as zip codes or counties. People can frequently move within and between these SUs for various purposes such as work, shopping, leisure, etc. The SUs are responsible for applying non-pharmaceutical interventions (NPIs) only within their borders to reduce the spread of disease during a pandemic. Like fluid flow from multiple sources to a single sink, a SU in each community is defined as the sink SU and paths between every SU lead to that.

The researchers use the modularity maximization problem with contiguity constraints (MCC). The model identifies communities of highly interconnected SUs within the geographic region boundaries based on the natural movement of people. The decision variables are assigning a SU to a community, choosing a SU as the sink in a community (binary variables), and the flow between two SUs within a community as a continuous variable. The objective is to maximize network modularity, a function of people’s mobility between SUs. The optimization model uses the natural movement of people as inputs to calculate modularity.

The scholars develop a mixed-integer quadratic-programming model (MIQP) to formulate the problem that can be solved on commercial optimization software. They also develop a heuristic to solve this problem. The heuristic algorithm is designed in three phases: new community creation, community expansion, and a local search for solution improvement. Finally, they consider North Carolina and South Carolina, two highly interconnected states in the U.S.A., as case studies to identify coordination zones.

The results show that the proposed heuristic algorithm as an initial solution can significantly boost the performance of the commercial solver to solve the MIQP model. Also, the proposed model identifies communities that are substantially better for coordinating pandemic-related policies than the existing geopolitical boundaries. Also, a ‘place-based approach’, where policies are customized and coordinated across interconnected locations, is effective in response to a contagious disease like COVID-19.

Infection transmission in a dynamic population: Rezapour et al. (2022) study the impact of non-pharmaceutical intervention methods to mitigate contagious infectious diseases in metropolises. They use a network design problem to model population mobility in which the traffic flow through the transportation system represents population mobility. The network’s nodes represent population structures in metropolises, and links show highways or main roads connecting urban areas. Three non-pharmaceutical interventions are investigated: movement restrictions, social distancing, and proactive testing/screening. They propose a two-step process in which isolation levels of nodes are determined in the first step,
and in the second step, the economic cost of the decision made in the first step is optimized. For each step, a model is developed. The first model selects the isolation level of each node to determine optimal isolation levels for the nodes of a mobility network to ensure that the number of infectious individuals at each node never violates its healthcare capacity. The second model selects the implementation levels of the social distancing at each node to minimize the economic cost of the social distancing for the metropolis’s population. Then, two heuristic approaches are developed to address the computational complexity of models to solve them for large-scale real-size municipalities. The research results show that imposing movement restrictions between sub-urban areas are only beneficial when they have different reproduction numbers. The social distancing reduces the infection peak in suburban areas, but its impact on the entire metropolis varies. The social distancing reduces a metropolis’ infection peak if its implementation disperses the reproduction number of the suburban regions. As allocation schemes of proactive testing/screening teams to sub-urban areas have intractable impacts on the infection peak, the best allocation scheme can be designed using optimization techniques.

Safe distancing and layout: Fischetti et al. (2022) study minimum social distance among people to ensure their safety during pandemics such as SARS-CoV-2. The research applies to customer-related businesses such as restaurants, offices, and theaters, regarding how to arrange their facilities (e.g., tables, seats, etc.) under distancing constraints. Inspired by the facilities’ location model used to locate wind turbines offshore, they propose a mixed-integer linear programming approach to account for the interference among installed facilities. As a result, the proposed model maximizes the total power production by selecting the appropriate location of facilities between potential candidates. Furthermore, they develop mathematical optimization algorithms to generate layouts that minimize the overall risk of infection among customers. Three practical examples are used to demonstrate the application of the model: (i) a restaurant (brewpub in Denmark) that has a certain space to place customer tables; (ii) the placement of umbrellas on a Venice beach; and (iii) locating seats in an amphitheater in Oslo. According to their computational results, the safest layouts often depend on the geometrical shape of the available area. Also, positioning as many facilities as possible on the border of the studied area reduces virus spread. Therefore, arranging facilities in the center of the area should be avoided because such facilities are surrounded by many other (potentially infectious) facilities in all directions.

4. Healthcare network configuration

Testing facility location and capacity planning: Liu et al. (2022) study locating testing sites to control the spread of COVID-19 to satisfy varying demands for test kits in large-scale emergencies like a pandemic. The decisions are (i) long-term, such as building a facility at a specific location (node), and (ii) short-term, which vary periodically, such as the available capacity of a facility, amount of relief supplies, and unmet demand of each node. The problem aims to identify the optimal location and capacity strategies during the entire time horizon to minimize the total operational costs, including construction, capacity expansion, transportation, and penalty costs.

The authors divide the problem into two phases: strategic and operational. Accordingly, a two-phase optimization framework is developed to solve the problem. In the first phase, the long-term variables (as the strategic decisions) are determined based on the predicted demand. Thus, a convex optimization-based Lagrangian relaxation approach is proposed to solve this problem. Furthermore, a heuristic gradient descent algorithm is suggested to solve the first sub-problem. In the second phase, the capacity to deal with demand fluctuation is adjusted dynamically. To do this, a dynamic capacity planning problem fulfills the requirements during the operational phase of each period. A heuristic adaptive dynamic allocation algorithm approach is proposed to solve the second sub-problem. The proposed two-phase framework effectively meets the varying demand caused by pandemics. The research suggests that if more facilities are built at the beginning of the planning horizon, the transportation cost and penalty cost of unmet demand are reduced while facing real-time demand volatility.

Testing Logistics Network: Wolfinger et al. (2022) present the Contagious Disease Testing Problem (CDTP) as a logistics problem. The research decides the number of operationalized test centers and their locations, the number of mobile test teams, assigning suspected cases to fixed or mobile teams, assigning specimens to the laboratory, and mobile test-teams routing. The problem is formulated as an arc-based mixed-integer linear programming model to minimize the total cost, including fixed costs and travel costs. A Large Neighborhood Search (LNS) metaheuristic is developed to solve the model. In addition, the researchers use a heuristic approach to repair the results of the LNS algorithm at each iteration. This repairing approach removes suspected cases from the solution until all cases are covered in a reasonable amount of time.

The authors use real-world data from two Austrian provinces to analyze the model in two ways: (i) using a mobile test team or (ii) using a stationary test team in a test center. The results show that considerable cost savings are typically linked with equally significant increases in the time taken to identify a suspected case. In other words, both restricting the duration between the time of occurrence of a potential case and the time of taking an infection detection test and restricting the time between taking a test and attaining its result can meaningfully increase the cost. Also, although a small percentage of suspected cases are not being clarified within the desired time, the proposed method can be applied in practice.

5. Healthcare resource allocation

Emergency Medical Stock and Capital: Zhang et al. (2022) study stock and capital reserve policies for emergency medical supplies against epidemic outbreaks at the regional level. The physical safety stock guarantees immediate availability of medical items when an emergency state occurs. On the other hand, the capital reserve ensures the immediately available capital to purchase further medical supplies in an emergency. Due to the high holding cost and perishable nature of medical products, the decision-maker (here, authorities and health organizations) decide about the optimal combination of safety stocks and capital reserves for emergency medical supplies against COVID-19, focusing merely on the reservation policy (and not the allocation of the reserves).

The authors consider an environment with a normal and then an emergency state. The environment begins in a normal state with a constant demand rate. Once it enters the emergency state, it stays there for an uncertain (random) time before returning to the normal state. The research proposes a joint reserve problem to minimize the expected long-run average cost using two decision variables: safety stock level and capital reserve level. A closed-form analytical solution is obtained for the problem. Accordingly, four decision-making regions are proposed: no reserves, safety stock only, capital reserve only, and mixed reserves. According to the results, more demand uncertainty sometimes leads to lower safety stock levels. In these situations, the combined reserves are grown by a large increase in capital reserves. Thus, the protection is increased by shifting from safety stock to capital reserves, but the risk of obsolescence is decreased. Also, they advise policymakers to consider using capital reserves next to keeping safety stocks strongly. This strategy can substantially reduce (obsolescence) costs while providing adequate protection.
Hospital Resource Planning Strategies: Fattahi, Keyvan-shokooh & Govindan (2022) study allocating healthcare resources to improve health systems’ response during the COVID-19 pandemic. Resources are categorized into two types in terms of patients’ usage: (1) direct in-use resources that a hospital assigns to a patient during hospitalization (such as ICU beds and ventilators) and (2) other service resources that a hospital utilizes (such as personnel and laboratories). The authors investigate the effect of three main strategies: (i) demand redistribution: transferring patients between regions to balance loads, (ii) resource relocation: sharing resources between regions to reduce capacity shortfalls in a particular area (such as healthcare personnel and ventilators), and (iii) resource allocation (extension): providing more external resources for regions or hospitals such as calling in additional personnel and new beds. The authors propose a multi-stage (periods are defined as stages) stochastic programming approach (MSPP), including healthcare resources planning and demand redistribution. A scenario tree construction approach captures the stochasticity of the number of infected individuals requiring hospitalization. An agent-based continuous-time stochastic approach is developed to care for multivariate stochastic parameters. Two COVID-19 case studies are investigated to examine the applicability of the proposed model: (a) ventilators sharing among a subset of the U.S. healthcare regions, and (b) demand redistribution and sharing resources among a subset of Iranian hospitals.

The results show the efficiency of the proposed method by in-sample and out-of-sample stability analysis. By sharing ventilators among regions of an area in the U.S., the demand for new ventilators is decreased about 58%. In the second case study, it decreases by about 17%. The main reason for this significant difference in these two cases is that the infection spreads at varying rates in different regions in the U.S. A case. Besides, the integrated strategies of sharing resources and patient transfers reduce the required resources by about 21% in the second case. Also, in both case studies, the recourse sharing strategy is more effective than the patient transfer strategy.

Hospital admissions and occupancy: Bekker, uit het Broek & Koole (2022) investigate hospital admissions and bed occupancy of COVID-19 patients in the Netherlands. They develop a prediction model to decide the required bed capacity to reduce relocations of patients created by the lack of capacity. The proposed model helps hospitals reserve the correct number of beds (i.e., ICU and clinical) for COVID-19 patients. They propose a model consisting of three steps. In the first step, the number of arrivals and occupancy of ICU and clinic patients are predicted according to historical data in the regions and hospitals. For this purpose, a linear programming model inspired by smoothing splines that incorporates weekly seasonality is proposed. In the second step, using the information on Lengths-of-Stay (LoS) of previous patients, the LoS distribution for new patients and the residual LoS for patients already present are determined. The Kaplan–Meier estimator is used to handle this step. In the third step, they balance patient admissions according to the number of available COVID-19 beds in each region and hospital. In this step, a queueing theory is used to translate current occupancy and predicted admissions into a prediction for occupancy. In this case study, the historical data is censored because some patients are still present; therefore, their LoS is unknown. The model can help regions and hospitals to reduce impact in terms of beds, i.e., the number of relocating patients between regions, and increase the remaining capacity for other types of care. From the accuracy of the predictions perspective, the proposed model outperforms the previous simple models based on three evaluation measures: weighted absolute percentage error (WAPE), mean absolute error (MAE), and root mean squared error (RMSE). The results show that the ICU occupancies’ predictions are accurate, particularly for three days ahead.

Hospital allocation: Hosseini-Motlagh et al. (2022) study the effect of emergency resources’ allocation in controlling a pandemic. They develop a new transmission-allocation model that allocates COVID-19 cases to health centers providing appropriate medical care. According to the illness severity and the background of patients, they are categorized into three groups: mildly ill patients (MIP), severely ill patients (SIP), and patients with underlying conditions (UCP). Also, different types of health facilities are considered, and patients are assigned to them according to their needs: i) isolation facilities, ii) general hospitals, and specialized hospitals. Isolation facilities do not present inpatient settings. They only isolate MIPs with stable conditions to prevent the spread of the virus. Hospitals provide inpatient care (such as oxygen therapy and ventilation) to unstable patients. The specialized hospitals service UCPs according to the patients’ special medical condition. The general hospitals serve SIPs; when the specialized hospitals are overwhelmed, they also accept UCPs.

The transmission rate is estimated using factors such as the contact rate, duration of the contact, age structure of the population, susceptibility to infection, and the number of transmission events per contact. To allocate COVID-19 patients to the health centers, the location of facilities, the number of cases allocated to different facilities, and the capacity of health facilities are decided to minimize the disease transmission.

As the number of suspected COVID-19 cases is considered uncertain, a multi-stage fuzzy stochastic programming approach is applied to allocate cases to health centers. Based on data from a case study in Tehran, results show that assigning patients to appropriate medical centers improve the performance of the healthcare system. Besides, behavioral changes and vaccination play a key role in curbing COVID-19 transmission. In addition, the population’s age structure affects the transmission rate of COVID – 19, and the older population significantly influences the transmission rate.

Ambulance dispatching: Rautenstrauss et al. (2022) study ambulance dispatching as one of the emergency medical service challenges during a pandemic. They consider two patient categories including infected and suspected, to analyze the effect of ambulance split in which the ambulances are designated to serve only other patient categories. Also, they consider an ethical justifiability concept in assigning ambulances. Due to ambulance split, patients who cannot be served by the nearest ambulance must accept longer waiting times, and a share of personnel assigned to infected patients must accept a higher mean infection probability. The assignment of ambulances to the per-category of patients is considered a decision variable. The researchers present a multi-objective model that maximizes (i) the minimum number of ambulances covering a node for all ambulance categories and (ii) the nodes’ coverages weighted by their share of emergency calls simultaneously. A two-stage approach is presented in which ambulance splits with the highest emergency call coverage are presented at the first stage. Then, the approximate Hypercube Queuing Model (AHQM) is used to evaluate the performance of the pre-selected ambulance splits at the second stage. The research proposes an Iterative Workload Approximation Algorithm (WAA) to solve the problem. WAA initializes with balancing the workloads of co-located ambulances of the same category by evenly distributing the sum of their workloads among them. Then, it distributes the workloads of overloaded ambulances to their direct backup ambulances.

Based on the real data from Munich’s ambulance dispatching center, long isolation times and high infection probabilities benefit patients and personnel because an ambulance split reduces the average response time without significantly increasing the mean infection probability for personnel. Although, disease-specific characteristics, such as isolation times or transmission probabilities, influence the decision of whether to split. In the case of short
isolation times and a low infection probability, the best average response times are observed when ambulances are not assigned to a certain category. Also, the general population could benefit from a split which indicates ethical justifiability when system workloads are high due to long isolation times or high infection probabilities.

6. Hospital operations

Ventilator Supply Allocation: Yin et al. (2022) investigate the allocation of essential resources, such as ventilators. Accordingly, they propose a risk-averse epidemics-ventilator logistic model considering untested asymptomatic infections, human movement among regions, and transmission rates for each non-pharmaceutical intervention (e.g., mask, social distancing, and lockdown). The researchers consider two weeks for each time stage as the incubation period (that means someone is infected but it is asymptomatic). They propose a multi-stage stochastic programming model to decide the number of ventilators allocated to each region at each time stage while minimizing the total tested symptomatic infected individuals and the number of deaths in all regions at all stages. The total budget for ventilators is considered a restriction in the model. Then, the authors suggest a scenario planning method to analyze the uncertainty of the proportion of untested asymptomatic infections at each time stage. The research shows that the main factors in allocating the ventilators to regions are the number of initial infections, disease transmission rates, initial ICU capacity, the population of a geographical location, and availability of ventilator supply. Also, human movement between regions significantly increases the transmission of the disease. So, the model reduces the movements between the regions by appropriately assigning ventilators to regions as a non-pharmaceutical intervention.

Dialysis machines: Bozkir et al. (2022) investigate how the available dialysis machines should be allocated to hemodialysis (HD) patients to serve different patient cohorts during a pandemic. The research considers four patient cohorts with an uncertain number that need dialysis each day: (i) uninfected acute patients admitted to the hospital that needs HD; (ii) uninfected chronic patients receiving regular HD treatment; (iii) infected COVID-19 HD patients; and (iv) suspected COVID-19 HD patients (there is a possibility of being infected). They propose the capacity planning problem of an HD clinic, which must allocate dialysis machines to different units serving different patient cohorts. Thus, the concept of “Overlap” is introduced in the model when two types of patients from different cohorts must be treated in the same HD session. A two-stage stochastic programming approach is proposed to decide the number of dialysis machines, the number of patients scheduled to receive HD treatment, the number of patients that cannot be served, and the overlap that exists while serving between uninfected, infected, and suspected patients. The objective is to minimize the total expected penalties that will occur over a week due to overlapping sessions of different cohorts.

In the first stage, capacity planning is decided to identify the number of dialysis machines allocated to the HD unit. Then, treatment scheduling decisions are made under different demand scenarios in the second stage. To do that, various equiprobable demand scenarios are generated, including demand realizations for each type of patient for each day. The model is tested on eight weeks of data from an HD clinic of a major public hospital in Istanbul. The results show that the clinic can use such an analytical tool to mitigate the infection transmission risk at the hospital by decreasing overlapping HD sessions among infected and uninfected patient groups.

Telemedicine in Hospital Operations: Zhou et al. (2022) study using telemedicine technology in hospitals during a pandemic. They develop a theoretical model to qualitatively analyze the joint impact of medical consumption and reimbursement on the hospital’s telemedicine strategy. The model considers three key concerns of the hospital in the current pandemic: (i) the differences in medical consumption between in-person and telemedicine modalities; (ii) the differences in reimbursement between in-person and telemedicine modalities; and (iii) the effort cost of infection reduction resulting from the pandemic. Also, they consider social welfare from the perspective of the social planner (government) using three factors: (a) the utility associated with each patient seeking care with modality, (b) an additional cost for each patient who refuses to go to the hospital, instead, care in person at home, and (c) the total costs incurred by the hospital.

They propose a monopoly healthcare market with a single hospital providing outpatient services for a population of routine (i.e., non-pandemic-related) patients with chronic diseases. The model considers the joint impact of the medical consumption difference, the infection-reduction effort cost, and the reimbursement difference on the hospital’s and social planner’s equilibrium telemedicine strategy. The objective function is to minimize the total cost. In the model, four cases are considered: (1) before the introduction of telemedicine with no pandemic (BN); (2) before the introduction of telemedicine with a pandemic (BY); (3) after the introduction of telemedicine with no pandemic (AN); and (4) after the introduction of telemedicine with a pandemic (AY). Also, decision variables considered in the model are selecting an in-person treatment method for all four cases (i.e., BN, BY, AN, and AY), telemedicine treatment method for AN and AY cases, and effort level for BY and AY cases.

Analysis of the model based on data from a cardiovascular hospital in Tianjin, China, shows that in the absence of the pandemic, the hospital prefers to use telemedicine when the differences in medical consumption and reimbursement are both small. But, during the pandemic, using telemedicine does not always benefit the hospital due to the negative influence of the pandemic on the hospital’s total costs. Furthermore, the hospital sets greater in-person capacity but less telemedicine capacity during the pandemic, which contradicts public beliefs. Also, social welfare is improved by introducing telemedicine when the cost of infection reduction and the difference in reimbursement is moderate.

7. Vaccine and testing kits

Planning testing and control strategies: Abdin et al. (2022) suggest an epidemiological model framework for policymakers as a decision support system. The model allocates testing and control resources to locations (hospitals and testing centers) to mitigate the spread of the COVID-19 pandemic. The model considers the possibility of asymptomatic exposure and infection and the distinct infection risk levels for different population segments. Thus, they divide the infected population into three groups: (i) infected asymptomatic (IA), where the disease is in the incubation period. These patients are likely to interact with other individuals without being noticed. Therefore, they have the highest disease transmission parameter (DTP), (ii) infected mildly symptomatic (ISM) that shows mild symptoms. They have a lower DTP because they are identified and isolated. (iii) infected severely symptomatic (ISS): they have severe symptoms, so they are isolated and require intensive medical care and attention. Their DTP is significantly lower but non-zero. The model minimizes the summation of newly infected and deceased cases who could not be hospitalized. A non-linear programming (NLP) optimization and simulation model are integrated. The optimization model intrinsically decides with the disease progression simulation. Furthermore, the authors use the current epidemiological simulation models in the proposed NLP model. So, the model not only simu-
lates the evolution of an epidemic over time within a population but also makes the mentioned decisions.

The model is validated to predict COVID-19 progression based on data from three major metropolitan regions in France. According to the results, the number of hospital cases reduces as more tests in testing centers are done. Also, the impact of mobility between regions, which affects how fast the disease transmits within a population, leads to the result that the resource distribution is not directly correlated to the population size. Therefore, to achieve equity, the allocation of the testing capacities shifts from the lower impacted regions to the higher impacted region compared to the standard solution.

**Vaccine and Testing Kit Allocation:** Thul and Powell (2022) study the allocation of vaccine and testing kits for COVID-19 to a set of geographical zones. They use the multi-agent sequential problem to decide the number of testing kits and vaccines allocated to each zone. They consider Provinces as zones when they want to solve the problem at the country level and define city regions as zones when the problem is defined at a city level.

The proposed model has an environment agent and two controlling and vaccination agents. The environment agent represents the epidemic system and does not make any decisions. Instead, the controlling agents collaborate to complete a joint goal of minimizing the cumulative number of new infections. The vaccination agent is responsible for allocating a dynamic stockpile of vaccines to zones, and the learning agent is responsible for allocating a dynamic stockpile of testing kits. In addition, a Direct Lookahead Approximations (DLA) policy is designed that uses a parameterized rolling horizon stochastic optimization technique to handle the demand uncertainty of the model. DLA is lookahead time strategies that optimize approximate models that look directly into the future.

The model is simulated to two scenarios: a resource allocation problem for each state in U.S.A. and another for the nursing homes in Nevada. In the U.S.A. simulation, the federal government has two agents corresponding with each other to administer a stockpile of vaccines and a stockpile of testing kits to each state (zones). But, during the height of a pandemic, there are likely to be extreme resource shortages in local areas, which may not be favored for allocations at the federal level. So, the second simulation considers a scenario where the state of Nevada has vaccines available for less than one percent of the nursing home residents and there is not enough testing capacity to test each of the 53 nursing homes in the state.

According to the results, the U.S.A. example demonstrates the model's scalability at the country level. Also, the nursing home example demonstrates the robustness under extreme resource shortages. Additionally, the model does not need any change when the environment agent is changed, i.e., all environment agents lead to the same model result. Also, the proposed modeling framework interacts with the environment when millions of vaccines and tests are allocated to populations of hundreds of millions. The research shows that the DLA policy can outperform other current policies during the COVID-19 pandemic.

**Vaccine Distribution Strategies:** Sinha et al. (2022) study vaccine distribution planning with a herd immunity policy. Considering that a vaccine is available, they assume that 67% of the population should be inoculated to achieve herd immunity. Accordingly, they try to effectively distribute vaccines among the masses to reach herd immunity against the infection quickly. First, they propose a demand forecasting model to minimize vaccine wastage due to expiration. Then, a cost-effective inventory model is presented under a no disruption scenario to fulfill forecasted demand. Finally, they propose an inventory model to minimize the total inventory cost comprising total ordering, inventory holding costs, and transportation costs of all the nodes over the planning horizon.

The authors develop a Stackelberg game-theoretic model to identify major disruption scenarios under which service level targets cannot be met. In the model, two agents, namely the leader and follower, have conflicting objectives. At the onset of disruption, the follower increases the order size to maintain the service level. The leader is aware of the follower's response and tries to identify a disruption scenario under which the follower's best response (maximization of order size within the permissible limits) will be insufficient in meeting service level targets. In fact, the leader and follower are two governmental initiatives considered competitors. The vaccine network program, which tries to reduce vaccine wastage, is interpreted as the leader, and the cold chain tracking program, which tries to prevent stock-outs and improve demand satisfaction, is interpreted as the follower. The Japanese Encephalitis (JE) vaccine distribution in Gorakhpur, India, is considered the case country to evaluate the effects of infrastructural deficiencies on achieving herd immunity targets for COVID-19 infection.

According to the results, strategic inventory reserve policy conditions cannot be practically implemented to meet service level targets. Structural overhauling may entail the installation of better cold storage facilities that do not reduce the vaccine's shelf life, purchasing more quality transport vans, improving the reliability of the transport network, and skills of cold storage managers by training.

As the Indian government is planning to eradicate the infection, ideally, a 100% service level is desired. Therefore, the demand for JE vaccine in a region is equal to the number of eligible children who have not been inoculated up till now. So, demand for the JE vaccine is forecasted according to the factors like birth rate, infant mortality rate, etc. In contrast, the objective of COVID-19 vaccine distribution is the attainment of herd immunity which can be achieved by inoculating 87% of the population.

8. Production and manufacturing

**Mask production planning:** Li et al. (2022) study mask production planning during the COVID-19 pandemic. Due to the demand for masks in the outbreak of COVID-19, they consider the demand uncertainty and propose a two-stage decision-making process: (1) in the first stage, before demand is disclosed, the design of the assembly line is determined, assigning a product to an assembly line station and installing a new station in the assembly line. A multi-item assembly line balancing problem (MALBP) minimizes the number of stations to install. (2) The second stage is a multi-item capacitated lot-sizing problem (MCLSP) that minimizes the total cost based on the inventory level of a product and backlog demand for a product.

The authors propose solutions to the problem, including two reformulation procedures and several sets of valid inequalities. The reformulation procedures decompose the problem into several mixed-integer sub-problems, and a tightened formulation is obtained by adding valid inequalities. Production and cost data are collected from five mask manufacturers during the COVID-19 pandemic in Beijing, China, for three types of masks: protective masks, surgical masks, and N95. The research results show that a larger investment in the first stage will establish more assembly line stations, leading to higher production rates. As a result, shortage costs due to unmet demand will decrease later.

9. Conclusion

In this special issue, 23 high-quality papers have been selected for publication. They include a wide variety of pandemic research problems and are formulated and solved using operations research methods to provide insights for practitioners and
academics. These papers are not expected to cover all subjects in the field of pandemics and epidemics. However, we observe that healthcare capacity planning, transmission and propagation and non-pharmaceutical have drawn more attention than others. In addition, some other areas can be considered by researchers using operations research techniques. Some of them are briefly introduced here:

**Surveillance & Early Warning:** A pandemic is usually triggered by just one or a small number of cases. Therefore, monitoring some anomalies via technical data (e.g., in-hospital records) or general data (like news and social media), can provide an early warning to speed up the process of disease containment. In addition, OR techniques for analyzing a small population can reveal some facts about an emerging outbreak.

**Data and Artificial Intelligence:** In the early stages of a pandemic, when some cases are identified positive, various data can be used to warn people or control their movements. For example, the affected people’s movements can be traced back via their credit cards, transportation card, etc. For example, various data mining methods can help us identify critical centers like some shops and restaurants to provide a basis for controlling them.

**Vaccine development:** After WHO officially announces a pandemic, many research organizations start research on product development to create vaccines or treatments. This process could be sped up. For example, some OR models can help WHO design an efficient incentivization mechanism like valuable awards, sharing vaccine profits, and shortlisting a few research centers with large financial support on each (or working with many small research centers with small support on each).

**Mass vaccination:** After a vaccine is introduced to the market, the most important issue is mass vaccination, in which millions of people should be inoculated as soon as possible. OR methods can help policymakers prioritize people and train volunteers to help healthcare workers.

**Developing countries:** Developing nations lack sufficient financial resources for their healthcare systems and also for buying vaccines. Of course, there has been some help from organizations like WHO COVAX (COVID-19 Vaccines Global Access), but it is insufficient. OR models may help WHO in designing rationing models more efficiently. Another issue is the lack of infrastructure in such countries. For example, the Pfizer COVID-19 vaccine needs a very low temperature in the transportation networks and warehouses. Such facilities are not available in some developing countries and isolated areas. Therefore, designing a cold supply chain network in which various vaccines, transportation modes, etc., are considered can be helpful.

**Commercial aspects:** The existing papers mostly focus on COVID-19 from a governmental or a healthcare system perspective. On the other hand, many issues from for-profit enterprises’ perspective are disrupted in case of a pandemic due to a lack of capacity for online ordering, home delivery, etc. OR models can help such businesses make appropriate decisions to recover faster.

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