From Data to Actions, From Observations to Solutions

A Summary of Operations Research and Industrial Engineering Tools for Fighting COVID-19

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Operations Research and Industrial Engineering (OR & IE) approaches are widely used and play important roles in improving the design and operations of many standard corporate activities such as supply chain management, job/staff scheduling, vehicle routing, facility location, and resource allocation. In the midst of the COVID-19 pandemic, policymakers, companies, community workers and individual households have been designing new systems and procedures to fight the virus. Many problems related to optimizing these systems and their operations can be tackled by extending the traditional OR & IE approaches with new objectives, constraints, and input data. The purpose of this document is to **summarize potential scenarios one may encounter during the prevention, disease control, intervention and recovery phases during COVID-19 outbreaks, and point out the OR & IE models that can be applied for solving the related problems**. We are not medical experts and thus will not focus on the drug & vaccine discovery, nor analyzing the disease transmission rate and its spread patterns. Instead, we consider decisions made by multiple stakeholders that can prepare for rare but catastrophic events such as the COVID-19 pandemic, can better inform the public to perform "social distancing", can better utilize resources and ensure medical supplies during the outbreak, and can improve the quality of life and work to mitigate economic losses.

The remainder of this report is organized as follows. In Section 1, we describe the overall lessons learnt from countries at different disease phases and summarize their effective/ineffective procedures when fighting the COVID-19. In Section 2, we focus on the disease prevention phase and describe what models can be applied to set up enough resources. In Section 3, we shift to problems related to controlling the disease during an outbreak and examine different industries that could be impacted due to diverse control policies. In Section 4, we consider the recovery phase and use today's China as an example to review possible issues and procedures for avoiding the rebound of infection numbers. Lastly, in Section 5, we conclude our report and list useful online resources for keeping up with data, guidelines, status updates about the COVID-19 pandemic.

1. Overall Lessons

As of March 24, 2020, the COVID-19 remains a global health crisis of grave and uncertain magnitude. We are at an unforeseen and unprecedented moment, and there is no doubt that fighting the disease requires global cooperation and teamwork. Figure 1 shows different stages (elaborated on the left-hand side of the figure) that major countries are going through and their total confirmed cases as of March 16, 2020.

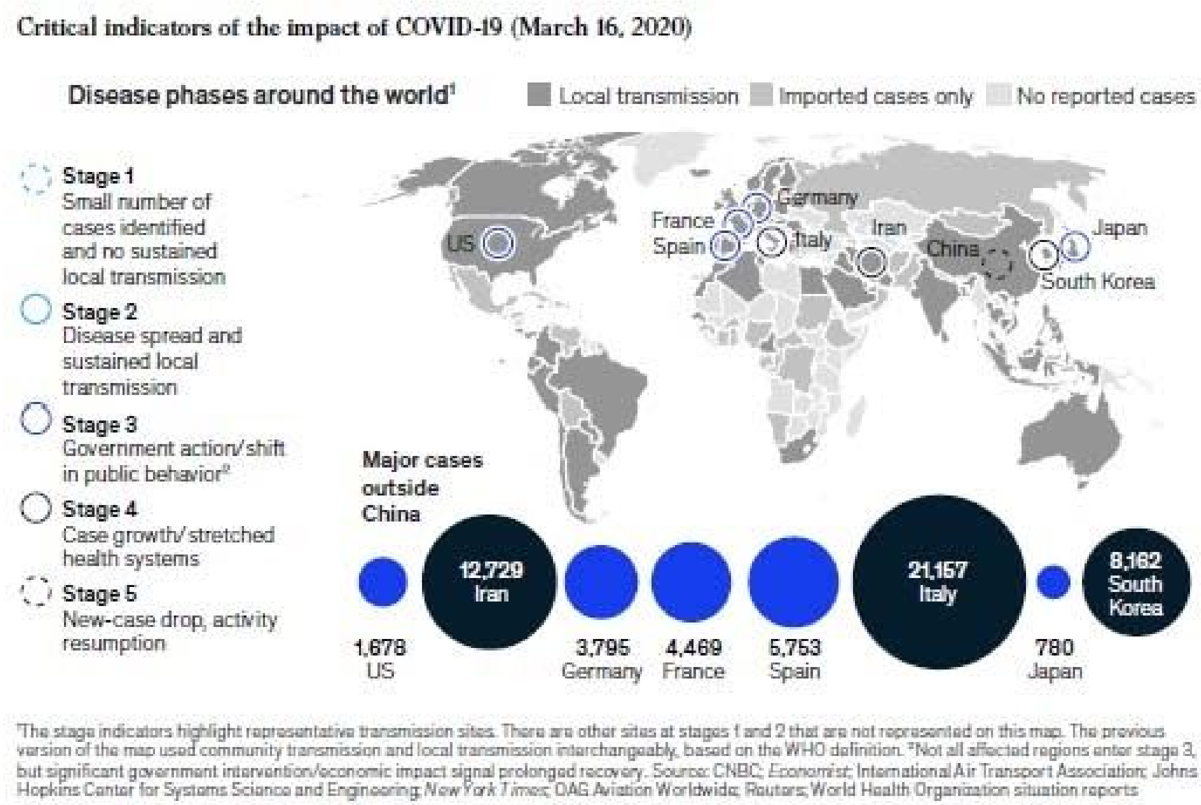


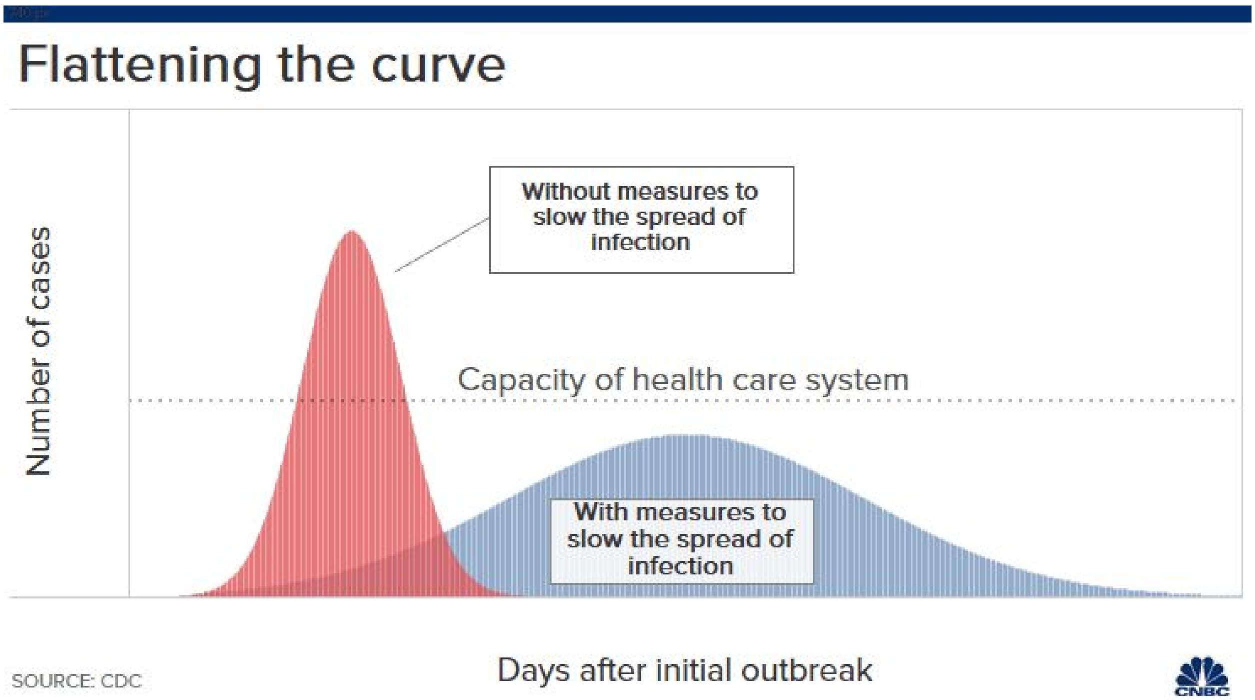
Figure 1: COVID-19 phases around the world (Source: McKinsey & Company)

Similar to Figure 1, one can find many articles online related to observation and prediction about the COVID-19 spread in different countries, but we found few on how to apply mathematical modeling and analysis to make more responsible and effective decisions. For example, the following two well disseminated articles published in Medium.com definitely raise public awareness about the severity of COVID-19 spread and about `social distancing' to hopefully `flatten the curve.'

- Coronavirus: Why You Must Act Now
  https://medium.com/@tomaspueyo/coronavirus-act-today-or-people-will-die-f4d3d9cd99ca

- Coronavirus: The Hammer and the Dance
  https://medium.com/@tomaspueyo/coronavirus-the-hammer-and-the-dance-be9337092b56

Up to this point, most of us are probably familiar with this `Flatten the Curve' picture which shows that intervention decisions can help with decreasing the total patient number and avoiding overwhelmed healthcare systems.



We, on the other hand, aim to provide descriptions about decision-making problems related to disease prevention, intervention, control and recovery and how to solve them using OR & IE tools. In other words, these models will allow policymakers, corporates, and other decision makers to **jump from the observations to solutions, and from data to actions**.

Since March 18, 2020, China has zero new local confirmed cases nationwide including in the city of Wuhan. A huge price is taken by shutting down all the economies for two months to fight COVID-19 spread. We summarize a few key lessons learned from China's lockdown and emergency response as follows, although not all of them can be borrowed by Western countries due to cultural differences.

1. **Enhancing community-based control of self-quarantine; tracking the paths of disease spread; warning people with potential high risk of infection.**

2. **Increasing COVID-19 testing availability and making information transparent to the public. (Testing! Testing! Testing!)**

3. **Avoiding medical supply shortage and avoiding exceeding healthcare capacity.**

4. **Triaging patients to avoid cross-infection in hospitals. Gathering all patients with mild symptoms to a central quarantine place for treatment.**

5. **Limiting travel and other non-essential activities, canceling social gathering, implementing `Shelter-in-Place' and `Stay-at-Home' policies.**

At the beginning of the COVID-19 outbreak, the Chinese suffered (e.g., having 5000+ new confirmed cases in Wuhan and 300+ death tolls daily for many days) from not implementing some of the above lessons learnt. As of March 24, 2020, China has 81807 cumulative total confirmed cases, 3283 death tolls, while there are a total 268,239 number of confirmed cases and 13,899 death tolls outside China. The latter happened quickly around the world since the very first patient was diagnosed in Italy in late February, and several outbreaks meanwhile appeared also in Iran and in South Korea. In the US, the daily newly confirmed cases have been skyrocketing in the past week, ranging from 4000 to 8000 per day. The total cumulative confirmed cases are 46,556 in the US and the death toll is 592 as of March 24, 2020. However, only 303,014 Americans have been tested. (All the figures are based on WHO, CDC and other online resources we later summarize in Section 5.1.)

In the following sections, we introduce OR & IE models for decision-making problems that can flatten the curve, centering around the above lessons.

2. Disease Prevention Phase

If a country is in either Stage 1 or Stage 2 shown in Figure 1, before the outbreak hits, policy makers can prepare more medical supplies, personal protective equipment (PPE), testing kits, and testing facilities. This will reduce the response time if the situation gets worse and enhance system resilience. In the stochastic programming literature, we classify decision-making processes into the `planning' phase (1st stage) and the `operational' phase (2nd stage). The planning phase is done before realizing the uncertainty, and the decisions are hard to be adjusted later. (In our problem, the uncertainty is the actual daily infection in each county/city/state/country due to the COVID-19 pandemic.) The operational-phase models our daily reaction and adjustment (called `recourse decisions') after the realization of the uncertainty is revealed. To understanding how to build a two-stage stochastic programming model and its solution approaches, we suggest a textbook:

1. **Birge, J. R., & Louveaux, F. (2011). *Introduction to Stochastic Programming*. Springer Science & Business Media.**

Moreover, a decision maker may have a risk-averse attitude towards preparing for disease outbreak, and instead of minimizing the expected long-run mortality rate in the objective function, one can choose other risk measures, e.g., the worst-case maximum daily death tolls, to minimize. This leads to the question about what types of objective function forms we can use when making decisions in uncertain and unknown environments, and we recommend the following textbook touching topics of robust optimization, risk-averse optimization, and stochastic programming:

2. **Shapiro, A., Dentcheva, D., & Ruszczyński, A. (2014).** ***Lectures on Stochastic Programming: Modeling and Theory*****. Society for Industrial and Applied Mathematics.**

Furthermore, decisions can be made sequentially over multiple phases (stages) but the computational complexity goes up very quickly because we need to examine all possibilities of the uncertain outcome in each stage, in order to determine the best policy. Both [1] and [2] above discuss multistage stochastic programming models and effective solution approaches.

2.1. Testing Facility Location Design and Testing Kit Distribution

One problem is where to locate COVID-19 testing facilities (i.e., which CVS, Walgreen, Urgent Care locations to use) and how to design their capacities (i.e., how many test kits they should receive daily and how to decide staffing levels in each facility). On one hand, we face unknown and uncertain demand volumes which depend on population density and prediction of the disease spread paths. We also know the distance and how convenient for individuals traveling to different location options. On the other hand, the testing facility locations should also depend on locations of factories who manufacture COVID-19 testing kits, their daily production capacity and where the factories are located. They should also depend on the locations of labs that can analyze the testing results.

The testing facility location design problem can be formulated as **an integer programming model**, where we can define binary variables representing whether or not each location (e.g., CVS store, Walmart parking lot) is a potential testing facility and we define integer variables to decide testing capacities in each location and shipment volumes between manufactures and potential testing facilities. We need to weigh in the total shipment cost from manufacturers to the selected testing facilities, and also traveling convenience from individuals to the selected testing facilities in the overall objective function. We also need to obey the testing facility capacities to avoid long lines which can also increase infection risk. Such a model can be solved during the prevention and preparation phase, and it can also be solved periodically during the disease outbreak phase (see Section 3) when we have new information about infected population distribution and/or new manufacturers.

For location design models, we suggest the textbook below for a comprehensive review:

3. **Daskin, M. S. (2011).** ***Network and Discrete Location: Models, Algorithms, and Applications.*** **John Wiley & Sons.**

A good example to demonstrate the importance of having ample testing facilities to prevent disease spread is Singapore. In close proximity to China, Singapore locates 800 testing facilities nationwide as early as early January, even before China declares national emergency. The robust infrastructure allows people to quickly get early tests and follow-up treatment, and effectively prevents virus spread. With 5.612 million people living in 270 square miles, Singapore only has 558 confirmed cases and 2 death toll up to the date March 24, 2020.

In Section 3, we will discuss problems that are relevant to other issues in testing facilities once they start to operate, including scheduling testing appointments, patient prioritization when the testing resources (e.g., testing kits, qualified labs and staff for analyzing the results) are limited, and also how to avoid long lines using queueing theories.

2.2. Healthcare and Other Relief Resource Preparation

Before disease outbreak happens, policy makers can prepare a list of designated hospitals in each county/state who can treat COVID-19 patients and this information can be released to the public, insurance companies and all types of healthcare providers. This will help reduce public panic. Moreover, medical supplies such as PPEs and critical equipment such as ventilators can be stocked for these hospitals so that we will have the immediate response ready when the situation gets worse.

The decisions of choosing hospital locations follow similar models used above for locating test facilities as we described in Section 2.1. We want those hospitals to have sufficient capacities (e.g., ICU beds, trained doctors and nurses) as well as they are convenient to direct patients to (e.g., shorter distance to most populations). The inputs for the facility location models now change to accommodate concerns that we have for selecting the best set of hospitals to put on the frontier for fighting the virus.

We will describe how to reform operations in these hospitals in Section 3.3 and how to ship medical supplies using supply-chain management techniques in Section 3.4. On the other hand, policy makers must allocate limited intervention resources quickly, in anticipation of where the outbreak is moving next. We recommend the following papers for prioritizing resource allocation plans before and during epidemics among diverse populations. These plans can be dynamically changed as we know more information about disease spread, the distribution of infected population and as we implement other disease intervention strategies described later in Section 3.1. In particular, the second paper below is more recent and covers both disease growth modeling (including behavioral dynamics and spatial correlation on a network) and resource allocation during epidemics. The case study included in the paper is on the 2014 West African Ebola outbreak. As mentioned by the authors, their methodology could be generalized to other disease outbreaks, including the Zika virus, and other interventions.

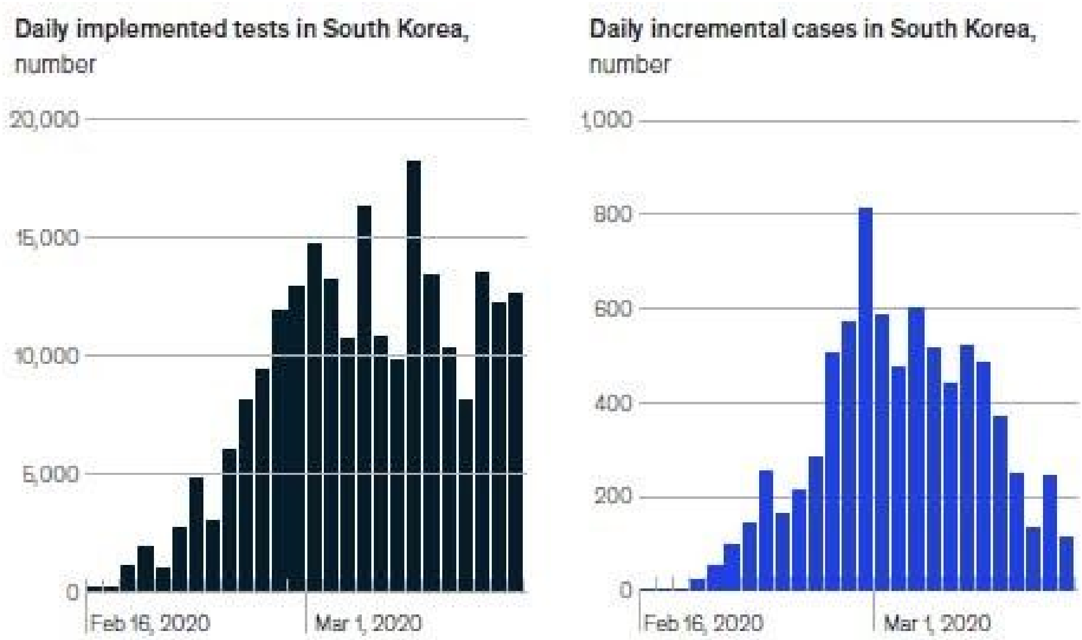
4. **Zaric, G. S., & Brandeau, M. L. (2002). Dynamic resource allocation for epidemic control in multiple populations. *Mathematical Medicine and Biology*, 19(4), 235-255.**

5. Long, E. F., Nohdurft, E., & Spinler, S. (2018). Spatial resource allocation for emerging epidemics: A comparison of greedy, myopic, and dynamic policies. *Manufacturing & Service Operations Management*, 20(2), 181-198.

3. During Disease Outbreak

3.1. Increasing Testing Ability and Information Transparency

The importance of making COVID-19 testing available to the general public cannot be over emphasized. For example, Figure 2 shows the number of tests implemented versus newly increased confirmed cases in South Korea during February 16, 2020 to March 1, 2020. With a significant increase at the beginning, South Korea implemented innovative ideas such as drive-through tests to scale testing drastically and completed more than 290,000 tests (around 10,000 tests per day for free) to find as many as COVID-19 infected cases. This significantly raises the public awareness and also provides more accurate information for policy makers to order enough medical supplies, etc., which are the decisions needed to be made in Section 3.2. On the other hand, take Michigan as the state I am living in as an example, as of March 23, 2020, only 3397 tests were performed among which 1328 are positive and the total population in Michigan is close to 10 million as compared to the 50 million population in South Korea. More testing kits need to be manufactured and distributed nationwide to better understand the COVID-19 outbreak situation so that policy makers can make right decisions and the public will behave more cautiously with the right guidance.



Source: KCDC; press search; WHO

Figure 2: Daily Implemented Tests vs. Daily Increased Confirmed Cases in South Korea

The same facility-location models we introduced in Section 3.1 can be used here with updated demand information. More testing kits need to be manufactured and the facility-location modeling can guide how to select manufacturing sites, so that we can more conveniently ship the testing kits to facilities in need. Furthermore, note that demand for testing can be largely impacted by where we locate testing facilities. Such a problem raises new technical challenges as we need to incorporate uncertain human behavior of testing into the traditional facility location models. We introduce the following paper that considers such decision-dependent uncertainty and seek distributionally robust facility location solutions when we do not know the exact probability distribution for characterizing this endogenous uncertainty.

6. **Basciftci, B., Ahmed, S., & Shen, S. (2019). Distributionally Robust Facility Location Problem under Decision-dependent Stochastic Demand. arXiv preprint arXiv:1912.05577.**

For patients' convenience of finding testing facilities, we can put their location information and real-time testing capacities online (e.g., through Google Map) so that we can maximally reduce the waiting lines and decrease infection risk. An example is the Baidu Map used in China that can show locations of urgent cases and hospitals in major cities in China that treat COVID-19 disease and how many beds they have. (In China, most people do not have primary physicians and directly go to hospitals if they are sick. This results in the difficulty of controlling patient flows in hospitals and skyrocketing confirmed infections in Wuhan due to cross-infection at the earlier stage of the disease outbreak and we will discuss the importance of patient triage in Section 3.3.)

3.2. Lockdown and Quarantine

During a disease outbreak, depending on different severity levels of virus spread, medical supply shortage, and prediction of future situation, policy makers need to dynamically decide what types of gathering events, stores, restaurants, and other public facilities to close, whether we close schools, and among the open facilities (e.g., groceries and pharmacies that provide life-support items), how to manage the inventory of essential items to prevent running out of stock, which will cause society panic.

A mathematical model can be built to select facilities to close given the frequency they are visited and how important they are to people's daily life. We can define binary variables to represent the decisions of whether or not to close each facility (if yes, then at what time), and build a model that minimizes the total infections while supporting people's daily-life needs. The inconvenience caused by facility locked-down can be multiplied by a certain weight and integrated into the objective function to be minimized as well. The resulting model is simply a so-called "Knapsack Problem" where each item has a value and a weight, and the goal is to maximize the total value of items put into a knapsack while we do not exceed the total weight limit. We recommend the following article for building such a static model for prioritizing facilities to lock down during pandemic.

7. **Deng, Y., Shen, S., & Vorobeychik, Y. (2013). Optimization methods for decision making in disease prevention and epidemic control. *Mathematical Biosciences*, 246(1), 213-227.**

Such a static model can be extended to a dynamic setting if we update the virus spread information periodically and make updated lockdown decisions sequentially. This will require the "multistage stochastic programming" model we mentioned at the beginning of Section 2.

Another way to cast the problem is to consider a Markov Decision Process (MDP), where the system is in different epidemic "states" and the "actions" correspond to different levels of intervention strategies ranked by lockdown scales and travel-ban strictness. In fact, it should be a Partially Observable Markov Decision Process (POMDP) because it is unlikely that policymakers can observe the true system state. Instead, the current number of infected cases and death tolls in the system only reflects the true system state "partially" with certain beliefs. The following paper further assumes that policymakers cannot accurately obtain transition and observation probability matrices needed in the POMDP, and proposes a so-called distributionally robust optimization framework to enforce robust policies for guiding our disease control actions. They test instances of an influenza epidemic control problem to demonstrate how to apply DR-POMDP results.

8. **Nakao, H., Jiang, R., & Shen, S. (2019). Distributionally Robust Partially Observable Markov Decision Process with Moment-based Ambiguity. arXiv preprint arXiv:1906.05988.**

Sometimes we may want to identify the most critical nodes (facilities visited by most people daily or workers such as doctors who may infect a large number of vulnerable populations if they are sick) so that we can provide extra protection during their normal operations or quarantine them if they are infected. We can use the `network interdiction' approach by treating the virus as `adversaries' and minimize the virus' maximum gain. The following paper discusses such a sequential-game model and the solution approaches.

9. **Shen, S., Smith, J. C., & Goli, R. (2012). Exact interdiction models and algorithms for disconnecting networks via node deletions. *Discrete Optimization*, 9(3), 172-188.**

We can also use integer programming to formulate a model to select nodes in a graph to `clean' when the virus moves around to infect non-quarantined patients (nodes). Note that some heuristic algorithms and cleaning strategies can be also applied, if we do not need to achieve optimality but prefer quick solutions.

10. **Penuel, J., Cole Smith, J., & Shen, S. (2013). Integer programming models and algorithms for the graph decontamination problem with mobile agents. *Networks*, 61(1), 1-19.**

3.3. Hospital System Reform and Operations

To face quickly increased infection cases, many existing hospital layouts and operations need to be reformed to avoid overcrowdedness and cross-infection. Many OR & IE problems are involved, ranging from ambulance dispatch, emergency staff planning, to hospital department clustering, an intensive care unit (ICU) bed allocation, and so on. For example, during the peak time of the COVID-19 outbreak in China, the department of infectious diseases in many hospitals cannot handle all infectious patients and we need to combine several departments to have enough space and resources for these patients. This step can be done in an early phase before the outbreak starts. Also, during a disease outbreak, it is important to make bed allocation decisions in ICUs of a hospital during periods when patient demand is extremely high. In the stage that patient demand is high and ICU has limited bed availability, when a patient arrives and no beds are available, a decision needs to be made as to whether the patient should be admitted to the ICU and if so, which patient in the ICU should be transferred to the general ward. Having enough ICUs and ventilators is critical for treating COVID-19 patients as about 20% patients reported so far have critical conditions. As an example, Germany has 132 deaths among all the 31,370 confirmed cases, close to 0.4% fatality rate, as compared to the nearly 10% fatality rate in Italy. One important factor is the highest ICU beds per 1000 population in Germany among all European countries. Here is a more detailed read about why Germany has low death rate from CNN:
https://www.cnn.com/2020/03/24/opinions/germany-low-death-rate-for-coronavirus-sepkowitz/index.html

Discrete-event simulation has been used as an effective tool for allocating scarce resources to improve patient flow, while minimizing health care delivery costs and increasing patient satisfaction in healthcare clinics. A representative work is:

11. **Jun, J. B., Jacobson, S. H., & Swisher, J. R. (1999). Application of discrete-event simulation in health care clinics: A survey. *Journal of the Operational Research Society*, 50(2), 109-123.**

3.3.1. Patient Triage and Admission Control

We can improve patient admission plans to avoid exceeding hospital capacities and especially the number of ICU beds that need to be reserved for patients with most critical conditions. The following papers discuss effective means used to prioritize which patients need to be admitted and how to triage patient flows in emergency departments. Both patient safety and operational efficiency need to be concerned. In the case of the COVID-19 outbreak, we also need to weigh in the safety of healthcare providers and minimize the risk that they are exposed to too many infectious patients per day by assigning appropriate shifts to doctors and nurses.

12. **Helm, J. E., AhmadBeygi, S., & Van Oyen, M. P. (2011). Design and analysis of hospital admission control for operational effectiveness. *Production and Operations Management*, 20(3), 359-374.**

13. **Saghafian, S., Hopp, W. J., Van Oyen, M. P., Desmond, J. S., & Kronick, S. L. (2014). Complexity-augmented triage: A tool for improving patient safety and operational efficiency. *Manufacturing & Service Operations Management*, 16(3), 329-345.**

14. **Saghafian, S., Hopp, W. J., Van Oyen, M. P., Desmond, J. S., & Kronick, S. L. (2012). Patient streaming as a mechanism for improving responsiveness in emergency departments. *Operations Research*, 60(5), 1080-1097.**

3.3.2. Capacity Allocation in ICUs and Different Types of Wards

WHO and CDC recommend to only treat patients with critical conditions in hospitals and suggest the ones with mild symptoms to be self-quarantined at home or in a central quarantine place (e.g., the temporary “Cubic Ship” hospitals (方舱医院) built in Wuhan, China that turn basketball stadiums into central places for treating patients with mild conditions) to avoid further disease spread.

Once patients are admitted to the hospitals, they can be divided into different types according to their severity. The wards for each patient type should be separated, and we need to decide how to allocate capacity (i.e., number of beds and medical staff) in each ward. Note that there are certain probabilities of patients transitioning from one type to another and each medical staff has their specialties and working-shift preferences. The paper below is recently published in a flagship journal discussing how to allocate beds in ICUs when the demand is extremely high. The approach can be generalized to study resource allocation in all types of healthcare units.

15. **Ouyang, H., Argon, N. T., & Ziya, S. (2020). Allocation of intensive care unit beds in periods of high demand. *Operations Research*. (https://doi.org/10.1287/opre.2019.1876)**

It is also important to consider whether to gather all mild-condition patients together and to build something similar to the temporary cubic-ship hospitals in China. It can help avoiding self-quarantine patients to infect their families and others if they quarantine at home and it also avoids them quickly changing to critical conditions without proper medical care. For COVID-19, because the infectious rate is relatively high and many cases show that patients with critical conditions die very quickly, it is meaningful to perform central quarantine procedures.

Moreover, [12] discusses ICU admission and discharge policies when the demand is really high, which is the current situation in Italy for treating COVID-19 patients. In the stage that patient demand is high and ICU has limited bed availability, when a patient arrives and no beds are available, a decision needs to be made as to whether the patient should be admitted to the ICU and if so, which patient in the ICU should be transferred to the general ward. [12] suggests a ratio policy which prioritizes patients according to their expected net benefit from the ICU (i.e., increase in survival probability as a result of being treated in ICU) divided by their expected length of stay.

We also suggest an earlier seminal work on this by OR experts who have a series of work published on ICU admission and discharge policies.

16. **Kim, S. H., Chan, C. W., Olivares, M., & Escobar, G. (2015). ICU admission control: An empirical study of capacity allocation and its implication for patient outcomes. *Management Science*, 61(1), 19-38.**

3.3.3. Locating Ambulances and Their Dispatch

The facility location model and other models in [3] introduced in Section 2.1 has been applied to locate ambulances for Emergency Medical Services (EMS). The ambulances can also be relocated during the emergency response processes as we receive new patient calls. The location and relocation problem can be tackled using two-stage stochastic integer programming since the decisions are binary/integer valued representing whether or not/how many ambulances we have close to each hospital. We suggest the following papers for the related OR models and solution approaches for such a problem.

17. **Brotcorne, L., Laporte, G., & Semet, F. (2003). Ambulance location and relocation models. *European Journal of Operational Research*, 147(3), 451-463.**

18. **Yoon, S., Albert, L. 2018. An Expected Coverage Model with a Cutoff Priority Queue. *Health Care Management Science,* 21(4), 517 – 533**.

Ref. [15] is more relevant to the COVID-19 outbreak as it considers the medical system being temporarily overwhelmed. There are prioritized calls for service in a congested system and the authors formulate new models to characterize policies when ambulances are held in reserve for high priority calls. When a system hits the "reserve" stock of ambulances, low priority patients are either diverted to neighboring EMS systems through mutual aid or added to a queue and responded to when the congestion has reduced. [15] finds that by adopting such an approach for sending (and not sending) ambulances to patients, this affects where we might want to locate ambulances.

Moreover, once locations of ambulances are determined, we may dispatch them dynamically and differently depending on patient conditions and how busy our current system is. We suggest the following paper on dispatching policies under mass casualty incidents (MCI).

19. **Dubois, E. Albert, L.A. 2019. Dispatching Policies During Prolonged Mass Casualty Incidents. Technical report, University of WIsconsin-Madison.**

Ref. [16] takes into account patients whose conditions deteriorate over time as they wait for service. The authors study how to dispatch ambulances during MCIs while allowing ambulances to idle with less emergent patients being queued. However, the inherent trade-off is that when low-priority patients are asked to wait for service, they can become high-priority patients. When high-priority patients are asked to wait for service, they can become critical or die. The key findings are, under the optimal policies, advanced life support ambulances often remain idle when less emergent patients are queued to provide quicker service to future more emergent patients.

3.3.4. Telemedicine Service Scheduling

During the COVID-19 outbreak in China, patients with mild illness were suggested to seek remote medical consultation at home during self-quarantine. The telemedicine platforms do not only offer timely treatment and guidance, but also effectively avoid cross-infections and long lines in the hospitals. For example, the link below shows a summary of online doctors and how to contact them both in Chinese and in other languages.
https://github.com/Support-WuHan/Online-Doctors-Info/blob/master/README-en.md

To successfully operate such a system, one needs to gather doctor volunteers, and get their information about available working hours, preferred time to provide the telemedicine service and also their medical expertise. The essential problem is a so-called `matching' and `assignment' problem used for assigning jobs, workshifts to factory workers. Meanwhile, working regulations need to be taken into account and be formulated as hard constraints for any feasible assignments. We also need to consider possible demand patterns and have enough doctors to cover the "hottest" lines. We recommend the paper below for how to set up a telemedical physician triage service system.

20. **Saghafian, S., Hopp, W. J., Iravani, S. M., Cheng, Y., & Diermeier, D. (2018). Workload management in telemedical physician triage and other knowledge-based service systems. *Management Science*, 64(11), 5180-5197.**

3.3.5. Medical Home Care Delivery

Medical home care delivery refers to a service that delivers certified nurses or medicines to patient homes rather than having the patients travel to hospitals to get them. Such a service can be provided to self-quarantine COVID-19 patients with mild symptoms and also to other patients who need to regularly visit their doctors' offices due to chronic disease. The latter are also the most vulnerable ones who have the highest fatality rate among all COVID-19 patients, and thus we should avoid them visiting hospitals too often to get cross-infection. Providing such a service can also alleviate some stress on the medical systems which need to focus on treating COVID-19 patients with critical conditions.

For goods, people and products delivery, the OR & IE communities have developed many fundamental models in the bigger umbrella term called `Vehicle Routing Problem.' It starts from the `Travel Salesman Problem (TSP)' which designs one shortest route for a salesman to visit a given set of locations. The VRP and its variants consider multiple vehicles to cover customer demand and each vehicle seeks a feasible route to visit a few customers so that we have the total traveling distance of all vehicles being minimized. We recommend the following two papers providing thorough review of basic VRP models, as well as optimization-based or heuristic approaches for solving the related integer programming models.

21. **Laporte, G. (1992). The vehicle routing problem: An overview of exact and approximate algorithms. *European Journal of Operational Research*, 59(3), 345-358.**

22. **Cordeau, J. F., Laporte, G., Savelsbergh, M. W., & Vigo, D. (2007). Vehicle routing. *Handbooks in Operations Research and Management Science*, 14, 367-428.**

We will discuss more vehicle routing and pick-up-delivery types of studies when describing OR & IE models for grocery delivery later in Section 3.5.

3.4. Supply Chain Management of Food and Essential Items

OR & IE researchers have worked on supply chain management problems for decades and examine almost all kinds of problems related to inventory control in retailers, warehouses, supply chain network design, shipment, and many more. Most of the time, warehouse facility locations, supply-chain network design, and warehouse-based inventory, shipment plans are highly correlated, and thus models that integrate a sequence of decisions are considered in the following papers, sometimes facing the customer demand uncertainty.

23. **Shen, Z. J. M., Coullard, C., & Daskin, M. S. (2003). A joint location-inventory model. *Transportation Science*, 37(1), 40-55.**

24. **Shu, J., Teo, C. P., & Shen, Z. J. M. (2005). Stochastic transportation-inventory network design problem. *Operations Research*, 53(1), 48-60.**

25. **Santoso, T., Ahmed, S., Goetschalckx, M., & Shapiro, A. (2005). A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research*, 167(1), 96-115.**

The well-cited book below summarizes strategies and case studies in supply chains.

26. **Simchi-Levi, D., Kaminsky, P., Simchi-Levi, E., & Shankar, R. (2008). *Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies*. Tata McGraw-Hill Education.**

In the recent COVID-19 outbreak, a severe retailing problem is the shortage of certain essential items, e.g., facial masks in Eastern countries and toilet papers in Western countries. (This also interestingly reflects the cultural difference and thus social behavior difference, which can be integrated in decision-making models considered before for all types of problems.)

One interesting phenomenon in supply chain management is the bullwhip effect, referring to "the final customer placing an order (whip) and order fluctuations building up upstream the supply chain. Much like cracking a whip, a small flick of the wrist (a shift in point of sale demand) can cause a large motion at the end of the whip (manufacturer's response)" (see Wikipedia). If the manufactures do not face temporary demand shortages of certain items rationally and build safety stocks ahead of time, the bullwhip effect will cause more severe shortage for the current period and unnecessary production in the future. For ways of mitigating and understanding bullwhip effects and factors that can impact the result, we refer to the following seminal papers.

27. **Lee, H. L., Padmanabhan, V., & Whang, S. (1997). The bullwhip effect in supply chains. *Sloan Management Review*, *38*, 93-102.**

28. **Lee, H. L., Padmanabhan, V., & Whang, S. (1997). Information distortion in a supply chain: The bullwhip effect. *Management Science*, *43*(4), 546-558.**

29. **Chen, F., Drezner, Z., Ryan, J. K., & Simchi-Levi, D. (2000). Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information. *Management Science*, *46*(3), 436-443.**

Moreover, empty shelves and shortages of essential items are only the visible impacts to consumers of the global supply chain disruption caused by the COVID-19 pandemic. Unseen are the stopping production in all factories across China in the past two months, in retail stores in Europe and in the US now and more months to come. Supply chain risk management has been an interesting topic to researchers for a decade, except that the COVID-19 outbreak is unprecedented in its scale and severity for supply chains of essential items, including food, medicine, and medical supplies. In planning to mitigate the risks of disruptions, the questions to ask are: should companies broaden their supplier choices (with more fees to maintain multiple contracts rather than a royal supplier)? How much inventory of raw materials and finished products should they stock to avoid severe backlog? The following article shares more detailed concerns:

`Coronavirus and Supply Chain Disruption: What Firms Can Learn'
https://knowledge.wharton.upenn.edu/article/veeraraghavan-supply-chain/

We also recommend two papers below on building mathematical models and analysis tools for achieving more reliable supply chains under the risk of disruptions. During the COVID-19 outbreak, such models are needed for manufacturing testing kits as well as other life-support essential items.

30. **Snyder, L. V., Scaparra, M. P., Daskin, M. S., & Church, R. L. (2006). Planning for disruptions in supply chain networks. In *Models, methods, and applications for innovative decision making* (pp. 234-257). INFORMS.**

31. **Cui, T., Ouyang, Y., & Shen, Z. J. M. (2010). Reliable facility location design under the risk of disruptions. *Operations Research*, *58*(4-part-1), 998-1011.**

3.5. Online Retailing and Grocery/Medicine Delivery

During city lockdown in China, digital technology and e-commerce become the key drive for helping people get food supplies, medicines, etc. In Wuhan — a city of 11 million people — initially, the lockdown imposed by the Chinese government triggered panic buying of food and emptying supermarket shelves. Quickly, online retailers team up with food and medicine suppliers, hire more delivers who were out of job during the COVID-19 break, and perform a series of procedures to make safe and timely delivery to people in the most need. The digitally enabled delivery system becomes resilient over the crisis, while earning profit for companies who react to this challenge, and sustaining tens of thousands of jobs. It also gains convenience for people who stay-at-home and ensures that fewer people need to expose themselves to infection risk while shopping for groceries.

However, in this blog, Prof. Alan Erera in Georgia Tech pointed out the issue of online retailing and on-demand delivery in the US. To respond to the scale of the delivery problem that COVID-19 causes in a modest-sized city in the US, we need to have better models, faster algorithms, and better prediction of demand. According to this Harvard Business Review article "Delivery Technology Is Keeping Chinese Cities Afloat Through Coronavirus", Alibaba's Cainiao network in China supports the supply chains via an AI-enabled digital inventory system that links the online and offline shopping worlds. As a result, almost as soon as the lockdown was declared in Wuhan, Alibaba was shipping medical and food supplies into the province. "*The combination of consumer digital maturity and digitally supported supply chains has enabled local residents to organize home delivery of essential supplies to people in self-quarantine. In the gated communities and neighborhoods that characterize Beijing, for example, residents have organized small groups of volunteers via group chat apps to receive supplies at the gate for the whole community, box them for each household, and deliver them to people's doorsteps.*"

Similar efforts are being seen in the US where Amazon and Walmart announce new hiring of workers in their warehouses and delivery trucks to hopefully respond to the shelter-in-place and stay-at-home orders. Other traditional grocery stores in the US are struggling with the new demand for online grocery shopping and delivery, such that their main businesses could be taken by Amazon who is more prepared. On the other hand, Amazon may consider collaborating with offline grocery stores and helping with their delivery businesses. The OR & IE models are very ready for pick-up and delivery, vehicle routing with time windows, and many other relevant problems, and these are not owned by Amazon - Uber, Lfty, Grubhub and many companies can consider helping and improving the delivery quality of Costco, Kroger, Safeway, Publix, etc. during the COVID-19 pandemic and city lockdown. We list the following papers as references for building models for food/medicine delivery.

32. Gendreau, M., Laporte, G., & Séguin, R. (1996). Stochastic vehicle routing. *European Journal of Operational Research*, *88*(1), 3-12.

33. Savelsbergh, M. W., & Sol, M. (1995). The general pickup and delivery problem. *Transportation Science*, *29*(1), 17-29.

34. Savelsbergh, M. W. (1992). The vehicle routing problem with time windows: Minimizing route duration. *ORSA Journal on Computing*, *4*(2), 146-154.

35. Bertsimas, D. J., & Simchi-Levi, D. (1996). A new generation of vehicle routing research: robust algorithms, addressing uncertainty. *Operations Research*, *44*(2), 286-304.

3.6. Airline Fleet Rescheduling, Call Center Staffing, and Airport Screening

As countries start to enforce travel bans during the COVID-19 outbreak, airline companies need to quickly react to them and make updated flight schedules, which will consequently affect the fleet management, crew scheduling, pricing and many more related problems. Example decisions involve what types of airplanes to be used to cover certain routes, what are the timetable for flying from origins to destinations, how to assign pilots and flight attendance in each flight, and new price for different legs. By defining binary or integer variables, one can formulate the above problems based on network flow balance, matching, covering and assignment types of constraints to satisfy hard requirements during airplane operations and crew management. Indeed, integer programming has been a vital modeling tool for solving resource allocation/schedule planning types of problems. The key here is how to efficiently obtain optimal solutions of huge integer programs and a well-studied method is so called `Branch-and-Price' which combines `Branch-and-Bound' and `Column Generation' ideas. A seminal paper is given below.

36. Barnhart, C., Johnson, E. L., Nemhauser, G. L., Savelsbergh, M. W., & Vance, P. H. (1998). Branch-and-price: Column generation for solving huge integer programs. *Operations Research*, *46*(3), 316-329.

We also list a few more papers and surveys on different problems in airline management, although they cannot cover all the past effort of solving complicated large-scale airline related problems.

37. Barnhart, C., Boland, N. L., Clarke, L. W., Johnson, E. L., Nemhauser, G. L., & Shenoi, R. G. (1998). Flight string models for aircraft fleeting and routing. *Transportation Science*, *32*(3), 208-220.

38. Barnhart, C., Hane, C. A., & Vance, P. H. (2000). Using branch-and-price-and-cut to solve origin-destination integer multicommodity flow problems. *Operations Research*, *48*(2), 318-326.

39. **Barnhart, C., Belobaba, P., & Odoni, A. R. (2003). Applications of operations research in the air transport industry. *Transportation Science*, *37*(4), 368-391.**

40. **Barnhart, C., Cohn, A. M., Johnson, E. L., Klabjan, D., Nemhauser, G. L., & Vance, P. H. (2003). Airline crew scheduling. In *Handbook of Transportation Science* (pp. 517-560). Springer, Boston, MA.**

41. **Schaefer, A. J., Johnson, E. L., Kleywegt, A. J., & Nemhauser, G. L. (2005). Airline crew scheduling under uncertainty. *Transportation Science*, *39*(3), 340-348.**

42. **Lohatepanont, M., & Barnhart, C. (2004). Airline schedule planning: Integrated models and algorithms for schedule design and fleet assignment. *Transportation Science*, *38*(1), 19-32.**

The travel-ban scale of the COVID-19 is unprecedented in modern transportation history and the challenge is about how to dynamically respond to the changes and post new routes and crew schedules in a very short time frame. For this, the branch-and-price-and-cut algorithm has been pushed to the limit of its computational power for equipping integer programming solvers like GUROBI and CPLEX. It is desirable to develop efficient approximation algorithms that can obtain solutions to the very large-scale global travel reduction problem in a few minutes, meeting demand in between specific regions during a short period (e.g., people try to return home before travel ban takes effect), and meanwhile achieve good empirical performance as compared to the true optimal result obtained by computing the integer programming model for hours or even days.

Furthermore, note that the call centers in airlines are dealing with unprecedented call volumes from people whose travel plans are affected. Many of them have immediate travels (e.g., within 72 hours) and their calls need to be taken with higher priority. Some have to travel in a few weeks or months and the travelers need to be better guided about when to make calls, what options they have at what cost, preferably via email first. This can greatly help reduce the workload in call centers and let the agents help the most urgent travelers first.

OR & IE models including integer programming, queuing models are well-developed for solving problems of large call center staffing, call selection and triage. The objectives involve achieving both high operational efficiency and service quality, which can be reflected on how many urgent and high priority calls were able to be served. We list a few papers below to show how different types of models and analysis can be used depending on specific problem contexts.

43. **Atlason, J., Epelman, M. A., & Henderson, S. G. (2008). Optimizing call center staffing using simulation and analytic center cutting-plane methods. *Management Science*, *54*(2), 295-309.**

44. **Ren, Z. J., & Zhou, Y. P. (2008). Call center outsourcing: Coordinating staffing level and service quality. *Management Science*, *54*(2), 369-383.**

45. **Whitt, W. (1999). Dynamic staffing in a telephone call center aiming to immediately answer all calls. *Operations Research Letters*, *24*(5), 205-212.**

46. **Harrison, J. M., & Zeevi, A. (2005). A method for staffing large call centers based on stochastic fluid models. *Manufacturing & Service Operations Management*, *7*(1), 20-36.**

Finally, airport screening is also an important link to the overall problem of handling short-term travel bans and an extremely overwhelmed number of returning travelers. Pictures of overcrowded international airports in the US after the government announced travel bans on flights between Europe and the US showed up on the internet everywhere, taking the headlines of all major press releases. Passengers were exposed to high risk of getting COVID-19 as they travel a long way and do not wear any protective masks squeezing in population-dense indoor space with other passengers. After 9/11, OR & IE techniques were developed for performing effective passenger screening in airports to reduce traffic while with high probability of identifying potential terrorists. We suggest reading the following papers about the problem of how to design risk-aware policies and multilevel check points for selectively screening passengers. Such a problem is highly relevant to the COVID-19 pandemic scenario as we want to dedicate the majority of staff and resources in airports to identify passengers and luggage with the highest chance of carrying a virus, while keeping shorter lines and waiting time for most passengers.

47. **McLay, L. A., Jacobson, S. H., & Kobza, J. E. (2006). A multilevel passenger screening problem for aviation security. *Naval Research Logistics (NRL)*, *53*(3), 183-197.**

48. **McLay, L. A., Lee, A. J., & Jacobson, S. H. (2010). Risk-based policies for airport security checkpoint screening. *Transportation Science*, *44*(3), 333-349.**

3.7. Work from Home - Allocating Enough Bandwidth

As most companies start the ``work from home (WFH)” policy, we need more bandwidth for high-quality internet service for teleconferencing and other virtual activities at home. This problem has been considered. For instance, Netflix and YouTube are cutting their stream quality in Europe to ensure normal use of other internet activities that are more work relevant, due to COVID-19 lockdown. Similar problem has been studied in the OR literature, where the Federal Communications Commission bought back spectrum from TV stations, packed the remaining broadcasters into a smaller swath of spectrum and sold the acquired spectrum to the wireless industry. The military can also use similar optimization strategies to allocate limited spectrum during combat operations when spectrum is scarce and communication vital. The underlying model is that of a graph-coloring problem with multiple side constraints. The problem can involve millions of variables and hundreds of thousands of constraints, and is typically formulated as an integer program, which can be tackled using combinatorial optimization theories, heuristics, decomposition algorithms, and constraint programming. We introduce a related paper in this area as follows.

49. **Kiddoo, Jean L., Evan Kwerel, Sasha Javid, Melissa Dunford, Gary M. Epstein, Charles E. Meisch Jr, Karla L. Hoffman et al. "Operations research enables auction to repurpose television spectrum for next-generation wireless technologies."** ***INFORMS Journal on Applied Analytics*** **49, no. 1 (2019): 7-22.**

3.8. Impact on the Low-income and Underserved

During the COVID-19 lockdown, families with low incomes will have difficulty affording child care as schools close, and students without internet access and a computer at home will not be able to keep up with schoolwork remotely. In the US, another issue related to school closures is the 30 million children who qualify for free or reduced-price lunch at school will have difficulty getting nutrition during school closure. To fight this, for instance, the Ann Arbor Public School still prepares lunches and uses school buses to deliver them to families in need. This website shows the current AAPS Food Distribution Plan with dates and locations to pick up the food.

The same OR & IE models we described in Section 3.3.5 and 3.5 can be used for designing the most convenient locations for families to pick up lunches within lunch time windows, and for designing the best routes for school buses to deliver lunches to these locations on time.

Moreover, many low-earning hourly workers do not have the option to work remotely, and this unexpected change in income will exacerbate challenges for families working hard to make ends meet. As we are facing drastically increasing demand for online food and medicine delivery, COVID-19 testing, and many other new issues during the COVID-19 pandemic, some workers can be hired to help staffing these businesses.

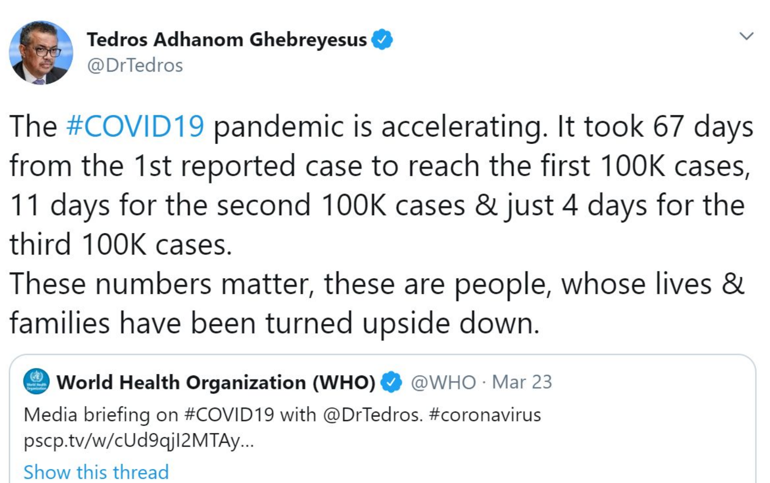
4. Recovery and Post-Recovery Planning

In late March 2020, China appears to be in the early stages of an economic rebound. While this recovery could be vulnerable given the ongoing pandemic globally, many Chinese companies have started their recovery and post-recovery planning. This Harvard Business Review article summarizes some lessons that can be broadly applicable in other countries once they enter the economic rebound phase and new business opportunities.
https://hbr.org/2020/03/how-chinese-companies-have-responded-to-coronavirus

Another critical issue faced by China now is the new wave of returning Chinese citizens mainly from European countries, UK, and US, who seek care at home but could meanwhile lead to new infections in mainland China, which have zero new confirmed cases for consecutive days since March 18. China has been shifting its focus away from containment to preventing foreign cases entering the country. It recently introduced a number of travel restrictions for visitors from high-risk countries. Effectively layouts in the airport and gathering international flights to a single destination for the ease of control are several related problems solved by Chinese policymakers and soon need to be considered by the whole world. The airport screening problem we describe in Section 3.6 is also a highly relevant problem in this context as we want to resume normal international travels as soon as possible for economy rebound, but need to make sure not to import new infections who are skipped and not quarantined. Such a ranking and selection problem is super important during the recovery phase and all countries need to cooperate to prevent the re-bounding of the outbreak.

5. Conclusion and COVID-19 Resources

In this article, we summarized OR & IE models that have been developed for corporate design and operations management, and explained how they can be applied and extended to solve COVID-19 related problems. We believe that with proper use of these models and efficient algorithmic design, we can allocate the most critical resource to the most vulnerable of the overall disease control process. It will allow policymakers to act more quickly and accurately to react to the pandemic.



“It takes 67 days to reach the first 100K confirmed COVID-19 cases worldwide, 13 days to reach the next 100K confirmed cases, and then 4 days to reach another 100K cases.” said by Dr. Tedros Adhanom Ghebreyesus, Director-General of the World Health Organization on March 23. (Today, April 2, 2020, worldwide we have over 1,000,000 infected cases and over 50,000 deaths.) Indeed, effective control and international cooperation are the keys to fight the virus and we hope that this document can provide references for guiding the needed system reform, redesign, and operations.

5.1. COVID-19 Data and Cases

Below we also summarize repositories of COVID-19 data, parameter estimates, cases, and tools for analyzing the data that we found online while we search for the OR & IE literature.

- A tool to visualize confirmed cases, death cases by country and lots of data resources https://ourworldindata.org/coronavirus

- This is a COVID-19 data center, tracking global cases and trends, maintained by a research group in Johns Hopkins University.
  https://coronavirus.jhu.edu/

- Daily updated links to view confirmed COVID-19 cases and death cases worldwide:
  https://www.bloomberg.com/graphics/2020-wuhan-novel-coronavirus-outbreak/
  And in the US:
  https://www.bloomberg.com/graphics/2020-united-states-coronavirus-outbreak/

- More detailed COVID-19 confirmed cases and test cases classified by county in the US:
  https://coronavirus.1point3acres.com/
  Chinese and Worldwide COVID-19 data live update (in Chinese):
  https://news.qq.com/zt2020/page/feiyan.htm#/global
  https://news.ifeng.com/c/special/7tPlDSzDgVk
  https://feiyan.wecity.qq.com/wuhan/dist/index.html#/

- A tool to visualize confirmed cases and their statistics (e.g., distributions by age, gender, nationality, or infection sources). As of March 21, 2020, Singapore only has 432 total confirmed cases and 2 death tolls.
  https://co.vid19.sg/dashboard

- An iterative model to visualize how intervention procedures can alter possible disease spread patterns and the number of infections.
  http://gabgoh.github.io/COVID/index.html

- Models of Infectious Disease Agent Study (MIDAS) Online Portal for COVID-19 Modeling Research https://midasnetwork.us/covid-19/
  It contains information and resources for COVID-19 modeling research, including a list of dashboard and visualization software, COVID-19 data and parameter estimates.

- Some links of data repositories for COVID-19 related patient data.
  https://github.com/CSSEGISandData/COVID-19 (by Johns Hopkins University)
  https://github.com/pcm-dpc/COVID-19 (by Italy government)
  https://datarepository.wolframcloud.com/resources/Patient-Medical-Data-for-Novel-Coronavirus-COVID-19
  https://datarepository.wolframcloud.com/resources/Epidemic-Data-for-Novel-Coronavirus-COVID-19

5.2. Other Online Resources

We also find a forum that posts a collection of related optimization problems and also COVID-19 treatment guidelines based on China's hands-on experience of treating COVID-19 patients.

A collection of optimization problems related to COVID-19 posted in an online forum:
https://or.stackexchange.com/questions/3644/are-there-any-covid-19-coronavirus-related-optimization-problems-with-input-da
(thanks twitter account @k_agpak to make me aware)

Handbook of Covid-19 Prevention and Treatment (Free Download)
https://covid-19.alibabacloud.com/

- This handbook summarizes lessons learnt from China's diagnosing and treating patients in different types, which can be extremely helpful for medical workers in other countries. Key contents including: (i) Technical strategies for preventing and treatment of the epidemic; (ii) Treatment methods to treat the critically ill; (iii) Efficient clinical decision-making strategies for frontline medical experts

A collection of all epidemiology related studies that have been published on SIAM journals. (They all involve mathematical modeling and data science.)
https://epubs.siam.org/page/EpidemiologyCollection

A SIAM blog that gathers related mathematical resources to help understand COVID-19:
https://sinews.siam.org/Details-Page/mathematical-resources-to-help-understand-covid-19

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