Ventilator Allocation Across Locations to Maximize Survival

Andrew M. Daw, David A. Goldberg, David B. Shmoys and Shane G. Henderson
School of ORIE, Cornell University

News reports make clear that there is a pressing need for ventilators everywhere that Covid-19 has surged. This has been a prominent issue in Governor Cuomo's daily updates on the situation in NY state. Governor Cuomo has stated that if the need had arisen (it now appears that NY state will have a sufficient number of ventilators) he would have directed ventilators from across the state to those hospitals in most dire need. Since the peak of the epidemic appears to be arising at different times in different counties across the state, such sharing can potentially greatly reduce the number of ventilators needed in the state.

We have developed a tool that can provide answers to questions like the following

1. How many ventilators are needed in the state during the pandemic, allowing that the pandemic peaks at different times in different locations throughout the state?
2. If the state faces a shortage of ventilators, then how should they be allocated to hospitals over time to minimize deaths?
3. In the late stages of the epidemic how many ventilators can we safely send to other states in need?

For all of these questions, the model can be updated from day to day to provide updated predictions and recommendations.

Related work explores this question in a similar manner, though it does not rely on as much real-time information, and has an objective function that is less clinically focused.

The tool requires the following inputs to generate its predictions and recommendations:

1. **Supply:** The number of ventilators within the state per day. This can increase or decrease over time to permit predictions under different assumptions about supply of ventilators.
2. **History:** The number of patients placed on ventilators by location and time to date. The term "location" here means a hospital or set of hospitals of moderate size, say greater than 100 ventilator beds. Smaller locations can be amalgamated to ensure suitable size.
3. **Potential Futures:** A small number (less than 20) of potential futures (aka scenarios) for how the epidemic might evolve across locations in the state. These are potential futures for which we need to plan, and can be obtained through consultation with epidemiologists.

Patients *may* be broken into groups defined by age and/or gender and/or co-morbidities, provided that sufficient data is available on how Covid 19 progresses for patients within each group.

The tool generates the following outputs to guide decisions:

1. The number of ventilators that each location should have each day. This then determines how many ventilators should be moved between locations each day.
2. The number of patients in each group, at each location, who should be placed on ventilators each day.
3. The predicted number of deaths, broken down by location and patient group, over the course of the epidemic, as a consequence of the above decisions. The model makes the number of deaths as small as possible.

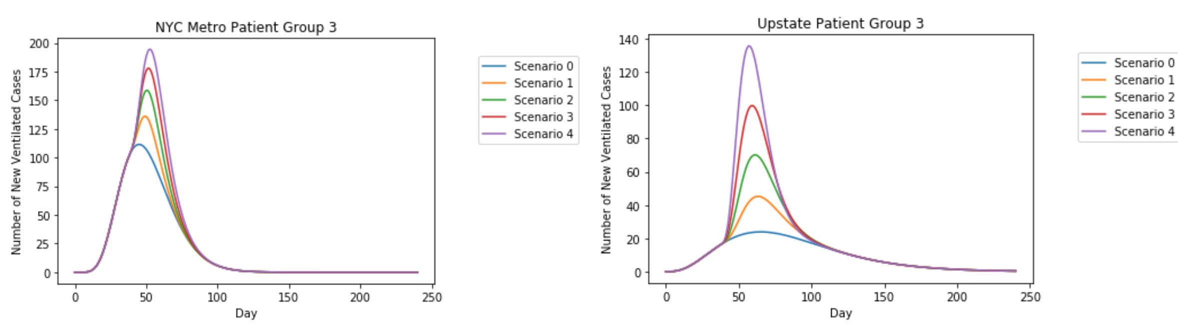
Hypothetical Case

As a **hypothetical** example of the usage of the tool we disaggregated NY state into two locations: NYC and the upstate area. The tool can work with many more locations, but the use of 2 locations makes this example more transparent.

There are 5 patient age groups: 0-17, 18-44, 45-64, 65-74, 75+.

1. **Supply:** 4600 ventilators with no increase or decrease throughout the epidemic, except in answering Q1 below, where we varied this number.
2. **History:** We used various data sources to obtain an approximation of ventilator allocation decisions up to April 7th. A key source was https://github.com/nychealth/coronavirus-data.
3. **Potential Futures:** We constructed 5 scenarios as depicted below. The upstate scenarios are exaggerated in size to ensure that shortages arise during the course of the epidemic in this hypothetical example.

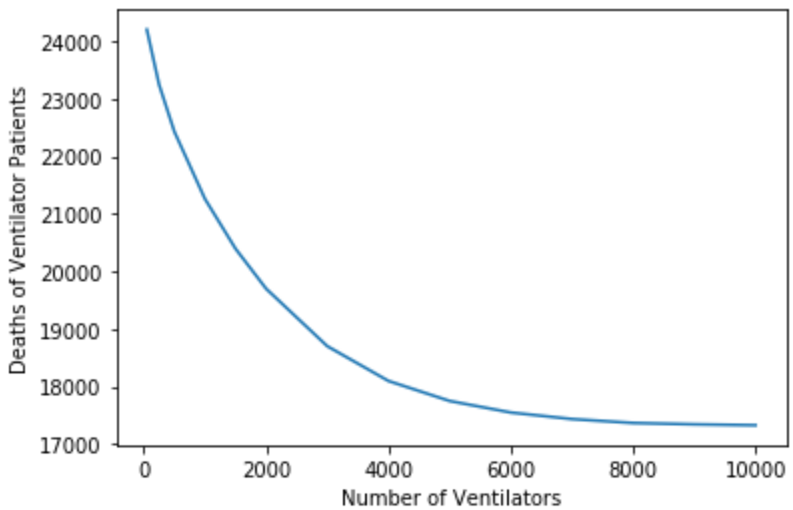
The scenarios for one of the patient groups in NYC (left) and upstate (right). Days are measured from March 1 (Day 1) onwards.



Questions and answers:

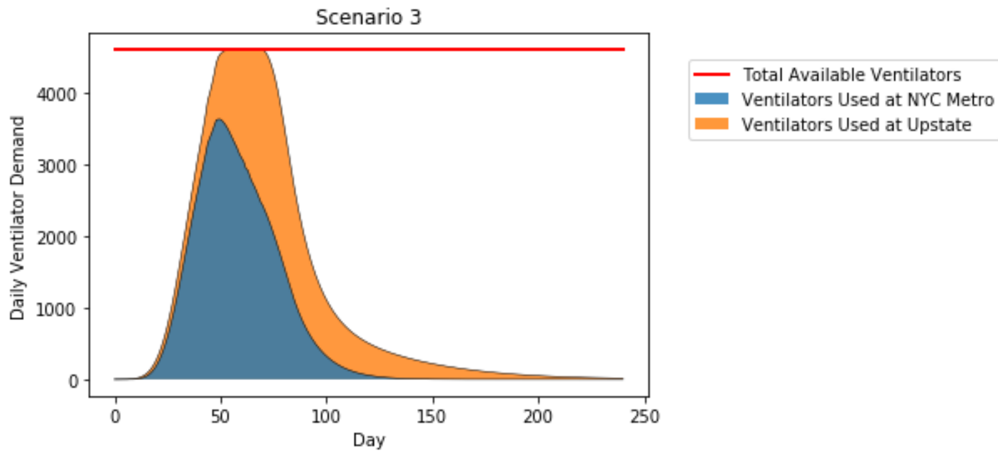
1. **How many ventilators are needed?**
Here is a plot of the estimated number of deaths over the entire course of the pandemic as a function of the number of ventilators. The number of ventilators ranges from as

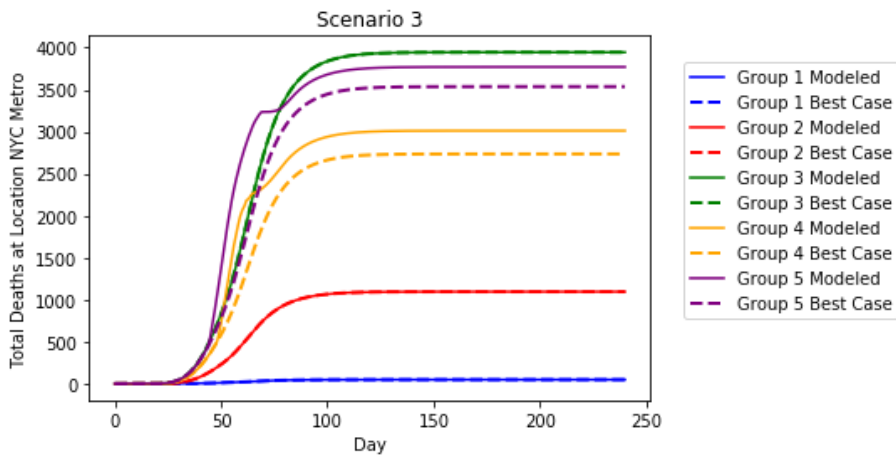
many as 10,000, enough to support even the most extreme scenario modeled, to as few as 50, at which point even the least vulnerable demographic is impacted. Due to the grim outlook for ventilator patients faced with shortages, the expected number of deaths increases very rapidly as the number of ventilators decreases. When there are fewer ventilators available, milder possible future scenarios are impacted, and this leads to substantial increases in fatality rates.

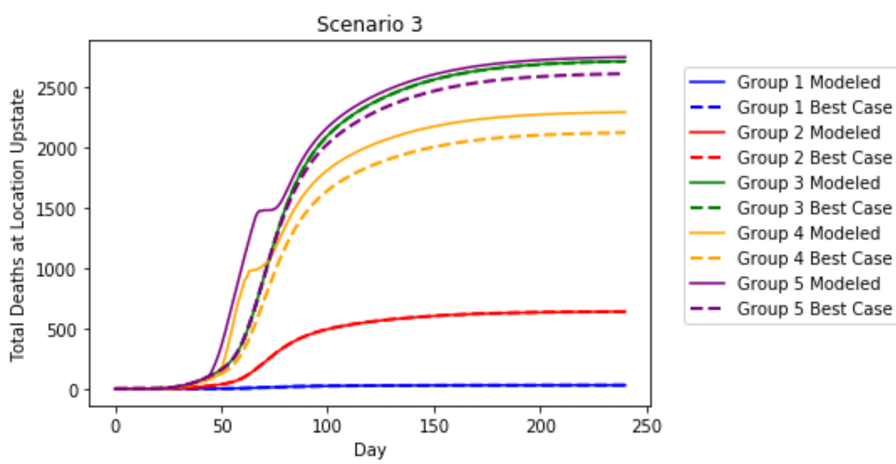


2. **How should ventilators be allocated across regions in the event of a shortage?** The plot below shows how ventilators can be allocated between the city and upstate over time. In practice we solve the model each day to get daily recommendations, but these predictions came from solving the model just once on Day 38 (April 7). This provides a prediction for the outcomes over the remaining epidemic. The peaks in ventilator need in the city and in upstate are predicted to hit at different times, which is exploited to reduce deaths by moving ventilators.

   We show results for just one of the scenarios. In this scenario a shortage hits around Day 50 that lasts for 20 days. The following plots show the number of ventilators assigned to the city and to upstate over time, the cumulative number of deaths seen over time in the modeled scenario (solid) versus a best case where there is no shortage (dashed) in NYC and in the upstate area respectively.

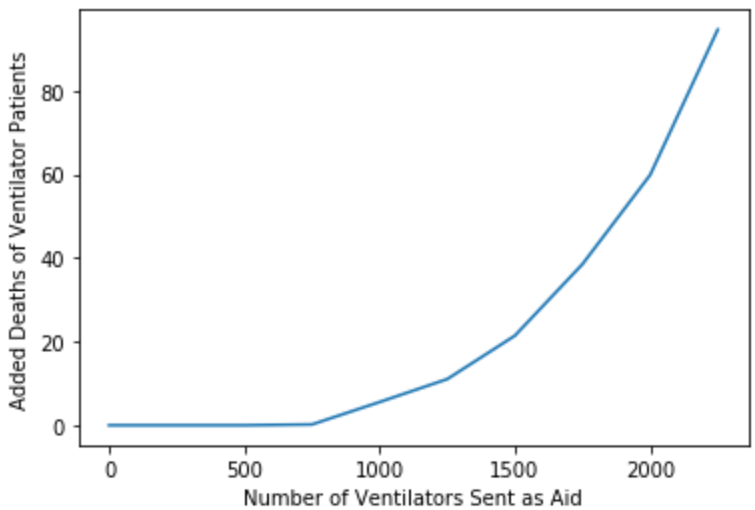




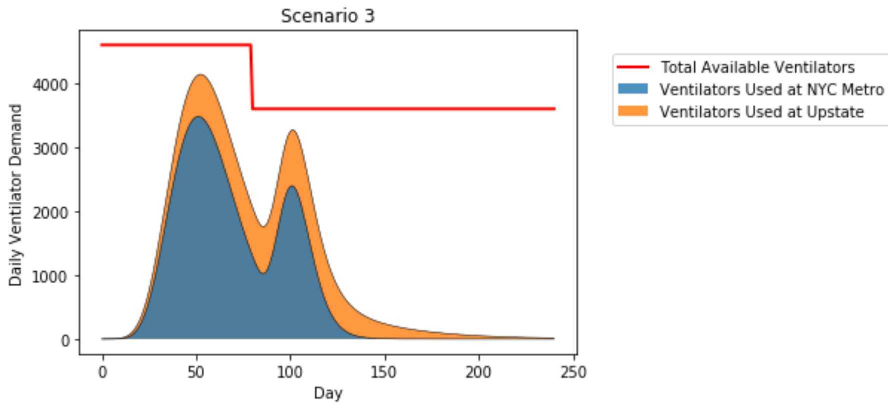


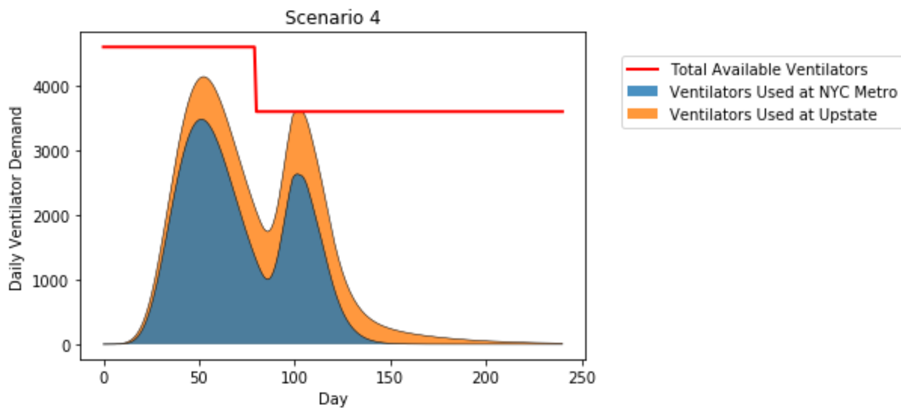
The latter two plots show the cumulative number of deaths in NYC and upstate over the course of the epidemic. The solid lines show what happens in the modeled scenario with a ventilator shortage. The dashed lines show the projected deaths in a separate unrealistic case where ventilator numbers are sufficient throughout the epidemic (the "best case"). The modeled death rate of Groups 4 and 5 surges around Day 50 relative to the best case due to a shortage of ventilators, yet the gap narrows by around Day 70. The reason is that many of those Group 4 and 5 patients still would have died, even if they had received a ventilator. They die later, even in the so-called “best case.” The gaps between the solid and dashed lines on Day 240 show the number of deaths caused by the shortage of ventilators over the entire course of the epidemic.

3. **How many ventilators can we safely send to other states in need?**
The plot below shows the estimated number of deaths as a function of the number of ventilators we send to other states on Day 80 (May 19). Given the initial stock of 4,600 ventilators, 750 ventilators can safely be sent without incurring additional deaths. However, as the number of ventilators sent away increases, shortages begin and the number of deaths increases as a result. Our scenarios allowed that there could be a “second hump” in the number of cases presenting after May 19 that is unknown in timing and size but all scenarios were modest in size compared to the past.



In this example, at an aid size of 1,000 ventilators there is not any shortfall for Scenario 3, the second most severe case. However, in the most extreme case, Scenario 4, the 3,600 remaining ventilators are not enough, as shown in the following pair of plots.


Scenario 3
Daily Ventilator Demand
Day
Total Available Ventilators
Ventilators Used at NYC Metro
Ventilators Used at Upstate


Scenario 4
Daily Ventilator Demand
Day
Total Available Ventilators
Ventilators Used at NYC Metro
Ventilators Used at Upstate