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Models for Assessing Strategies for Improving Hospital Capacity for Handling Patients during a Pandemic

Bahar Shahverdi, MS[1]; Elise Miller-Hooks, PhD[1,*]; Mersedeh Tariverdi, PhD[2]; Hadi Ghayoomi, MS[1]; David Prentiss, MS[1]; Thomas D. Kirsch, MD, MPH[3]

[1]George Mason University, Sid and Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering, Fairfax, VA, USA
[2]The World Bank, Washington, D.C., USA
[3] National Center for Disaster Medicine and Public Health, Uniformed Services University, Bethesda, MD, USA

***Correspondence to:** Elise Miller-Hooks; E-mail: miller@gmu.edu.

Short Running Title

Models for Improving Hospital Capacity

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Abstract

Objective:

The aim of this study was to investigate the performance of key hospital units associated with emergency care of both routine emergency and pandemic (COVID-19) patients under capacity enhancing strategies.

Methods:

This investigation was conducted using whole-hospital, resource-constrained, patient-based, stochastic, discrete-event simulation models of a generic 200-bed urban U.S. tertiary hospital serving routine emergency and COVID-19 patients. Systematically designed numerical experiments were conducted to provide generalizable insights into how hospital functionality may be affected by the care of COVID-19 pandemic patients along specially designated care paths under changing pandemic situations from getting ready to turning all of its resources to pandemic care.

Results:

Several insights are presented. For example, each day of reduction in average ICU length of stay increases intensive care unit patient throughput by up to 24% for high COVID-19 daily patient arrival levels. The potential of five specific interventions and two critical shifts in care strategies to significantly increase hospital capacity is described.

Conclusions:

These estimates enable hospitals to repurpose space, modify operations, implement crisis standards of care, prepare to collaborate with other health care facilities, or request external support, increasing the likelihood that arriving patients will find an open staffed bed when one is needed.

Keywords: COVID-19; SARS-CoV-2; Hospital capacity management; Intensive care; Infectious patient care

List of Abbreviations

Adapted Standards of Care (ASCs)
COVID-19 Hospital Impact Model for Epidemics (CHIME)
Coronovirus Disease (COVID-19)
Critical Decision Unit (CDU)
Critical Event Preparedness and Response (CEPAR)
Discrete-event Simulation (DES)
Emergency Department (ED)
Internal General Ward (IGW)
Emergency Severity Index (ESI)
Intensive Care Unit (ICU)
Johns Hopkins Hospital System (JHHS)
Leaving Without Treatment (LWOT)
Length of Stay (LOS)
Mass Casualty Incident (MCI)
Nonpharmaceutical Interventions (NPIs)
Operating Rooms (ORs)
Personal Protective Equipment (PPE)
Post Anesthesia Care Unit (PACU)
Surgical Intensive Care Unit (SICU)
World Health Organization (WHO)

1. Introduction

On January 30, 2020 a Public Health Emergency of International Concern was declared by the World Health Organization (WHO) due to the Coronovirus disease (COVID-19) pandemic. Nonpharmaceutical interventions (NPIs), such as social distancing, masks, and limiting social and economic activities, have proven effective in reducing transmission, but have been applied variably and inconsistently. As a result, hospitals see demand fluctuations and must adapt by repurposing space, mobilizing resources, and modifying care when conditions warrant and then return to normal operations to serve routine patients, including emergency patients, when excess demand diminishes.

To support health care response to the COVID-19 pandemic, Currie et al.[1] discussed how simulation modeling techniques, such as system dynamics, agent-based modeling, and discrete-event simulation (DES), can be applied to tackle challenges to hospitals caused by COVID-19 and Wood et al.[2] proposed a stochastic DES framework for modeling Intensive Care Unit (ICU) operations. They tested various strategies, such as increasing the number of beds, decreasing length of stay (LOS), and flattening peak demand, for reducing deaths caused by insufficient ICU bed capacity. Results of their work indicate that mortality resulting from ICU capacity shortage could be reduced by up to 90% (from 3,780 to 382) through a combination of strategies. A current tool, COVID-19 Hospital Impact Model for Epidemics (CHIME)[3], uses an epidemiological model to aid hospitals in capacity planning. CHIME projects daily numbers of admitted pandemic patients based on the population in the surrounding area, the hospital's market share, assumptions about the spread and behavior of the virus, average length of stay of pandemic patients, and other parameters.

Herein, systematically-designed, numerical experiments were conducted using whole-hospital, DES models with incorporated COVID-19 patient flows. The models account for the hospital-wide impacts of bottlenecks arising in units that are not captured in single-unit (ICU) models [2], and can take as input demand estimates from models such as CHIME. Experiments were devised to capture the varying pandemic circumstances arising over place and time and how the circumstances impact hospital performance.

This paper assesses potential strategies for increasing hospital capacity to handle demand surges and considers the timing for implementing and withdrawing these strategies as surge demand ebbs and flows. These outcomes have broader implications for other infectious disease outbreaks.

2. Methods

This investigation uses whole-hospital, resource-constrained, patient-based, stochastic, DES models of a generic 200-bed urban U.S. tertiary hospital serving routine emergency and COVID-19 patients. DES has been used widely over decades to inform hospitals and other healthcare entities in support of operational decisions, including, for example, personnel and procedure scheduling, bed capacity and admissions management, equipment deployment, capital investment and possible patient flow improvements [4,5,6].

The models used in this paper were constructed on previously developed models that formed the basis for a series of prior, pre-COVID-19 hospital performance studies[7,8,9]. These prior works investigated the importance of taking a whole-hospital, resource-constrained and patient-based approach. Tariverdi et al.[7] also studied the impact of modified operations and adapted standards of care (ASCs[10]), such as the cancellation of elective surgeries, in coping with surge demand as might arise from a slow-onset event, such as a severe flu season, or sudden-onset disaster event, such as a Mass Casualty Incident (MCI), on hospital capacity and capability. The previous models were expanded to include 12 (from 10) critical treatment units with adapted workflows and altered plans for space and resource utilization as needed to incorporate COVID-19 patient care.

Four surge levels are considered that correspond with changing COVID-19 pandemic conditions of the hospital's service area: Getting Ready, Initial Onset, Outbreak, and Hot Spot. Getting Ready involves ordinary operations and standards of care without pandemic patients. Initial Onset and Outbreak levels involve the integration of added care paths specific to infectious (COVID-19) patients while a hospital continues to serve routine emergency patients. The level moves from Initial Onset to Outbreak when the design and preliminary ASCs cannot support the incoming patients and additional care path modifications are required. The specification of ASCs by surge level are given in Table 1. The Hot Spot level is necessary if pandemic patient arrivals continue to surge and prior changes and ASCs are insufficient. This Hot Spot level presumes that nearly all hospital resources are turned toward pandemic patient care and all reasonable modifications and care alternatives, including ASCs, are taken. Routine emergency patients will be turned away or even transferred out, creating a COVID-19 only care facility[11,12,13]. External support will be required to create additional capacity.

Systematically designed numerical experiments, findings from which are reported herein, suggest how overall hospital functionality, as well as the performance of specific hospital units, will be affected by the care of pandemic patients along specially designated care paths under changing surge levels. Details of these findings, along with insights for action as might inform policy, are presented in Section 3.

Plans for implementing hospital capacity enhancements to cope with the increasing demand can be made by estimating the COVID-19 patient arrival rates at which each surge level is reached. These transitions are referred to herein as switch points. This study identifies the switch points for the illustrative hospital for both increasing and decreasing cases. As surge demand recedes, modifications can be relaxed to again begin to serve routine emergency patients with usual levels of care.

2.1 The Simulation Framework

The base hospital model includes 10 critical units: Emergency Department (ED) including triage, Intensive Care Unit (ICU), Surgical Intensive Care Unit (SICU), Stepdown, Operating Rooms (ORs), internal general wards (IGW), ED Trauma, Preop, Post Anesthesia Care Unit (PACU), and laboratories. The model is resource constrained and patient based. Limited resources, including doctors, nurses and beds, are specialized and tracked. Patient care paths begin from entry to the ED and end at hospital discharge. The care path assigned to a patient is a function of the injury or illness described by an Emergency Severity Index (ESI), a validated indicator of severity and health outcome [14]. Patient treatment priorities in the model are consistent with their ESI levels and time spent waiting, and follow settings from prior works [8,15]. Patient survival times are a function of time spent waiting to receive the first critical service within their care paths.

The chosen modeling approach recognizes that the functionality of a hospital and its individual units depend on interconnections between units. These dependencies are both direct, as backups in one unit can cascade to another, and indirect, as a consequence of overlap in patient care paths and patient resource needs.

Model details were built based on extensive interviews with the director of operations and an administrative director of ED/trauma, safety, security and employee health services, head nurse, and others, at the Johns Hopkins Hospital, Johns Hopkins Suburban Hospital, and Johns Hopkins Office of Critical Event Preparedness and Response (CEPAR)[16]. Parameters that could not be obtained from these interviews were developed from national averages and values from case studies in the literature [8].

To test the validity of the developed models, multiple numerical experiments were designed and implemented. Through experimental runs under routine conditions, model outputs were compared against averages from similar Trauma-level I and II hospitals. Unusual model behavior was investigated and refinements to model details were made and parameters were adjusted through further discussion with hospital experts. This process of model construction and verification is described in more detail by Tariverdi et al.[8].

2.2 Incorporating Protected Care Paths for COVID-19 Patients and the Four Surge Levels

The basic hospital model was redesigned to incorporate COVID-19 care paths and accompanying work flows, special equipment including ventilators and personal protective equipment (PPE), modifications to operations, including repurposing of hospital space, and the application of ASCs as employed in a typical U.S. urban tertiary hospital. Care flows and parameters specific to COVID-19 were designed from information obtained from discussion with hospital administrators and other health professionals, including nurses, personnel involved in modifications to the hospitals to change workflows, and modelers, across several hospitals beginning early in the pandemic. As protocols and work flows changed as the pandemic progressed, specific COVID-19 patient arrival rates and related reductions in routine emergency patient arrivals were replaced with systematically chosen combinations over a range, and a generic approach to handling COVID-19 patients was adopted.

The Getting Ready level assumes few or no COVID-19 patients. As the number of COVID-19 patients increase to reach the Initial Onset level, work flow changes to meet rising pandemic patient demand. To model this, COVID-19 patients are presumed to enter the hospital through a separate ED Critical Decision Unit (CDU). This protects other unexposed ED patients. Following a probability distribution, a percentage (10% in the experiments) of these patients are assigned an ESI level of 1 and are sent directly to the ICU. After ED testing and observation, the remaining patients are either admitted (60% to isolation rooms) or discharged (40%). At Initial Onset and Outbreak surge levels, IGW and a limited number of ED beds are repurposed for isolation of admitted COVID-19 patients. In the test hospital model, 70 isolation beds were created from 20 ED beds and 50 IGW beds.

At low COVID-19 patient arrival rates, routine emergency patient demand is presumed. Routine emergency arrivals decrease as COVID-19 patients increase, either because patients forgo hospital visits to reduce their exposure or because capacity for these patients is limited, creating long wait times and potential need to turn patients away[17,18]. When reaching a Hot Spot surge level, almost all resources are repurposed to expand the capacity of the COVID-19 care paths; in this model, half of the ED, all IGW and Stepdown beds, and related staff are used to expand the capacity of the isolation rooms. ED beds, nurses and doctors are also added to the ICU (Table 1).

2.3 Numerical Experimental Design

The hospital models were coded in Extendsim 10[19], a microscopic simulation platform designed for generic queueing applications. This software is highly flexible, allowing direct coding of all elements, uncertainty modeling and the monitoring of dynamically varying performance characteristics.

To create generalizable findings, systematically designed numerical experiments were conducted (Table 1). Each simulation run replicated 62 days, the first 20 days of which are the warm-up period during which the simulation outputs reach a steady state. The outcomes (random variates) of random variables, each representing an activity, such as time spent by a single patient in the ED, depend on a sequence of random numbers, governed by an initial seed value given to the random number generator. Each seed begins a specific stream of random numbers and, thus, a specific realization of the random variables for which a single performance outcome (random variate) is obtained. Run again on a different seed, the simulation will produce a second performance estimate. This variability is desirable, as it allows for the occurrence of a range of situations and behaviors and can capture day-to-day variabilities seen in reality. Each run design was repeated over 250 seeds, which was chosen based on tradeoffs between confidence interval stability over the many variables and computational burden as determined from experiments with between 10 and 5,000 seeds per run batch.

Note that as the study had no human data, it was exempted from Institutional Review Board review.

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3. Results

Key findings from this analysis involving Initial Onset, Outbreak, and Hot Spot surge levels are synopsized in Table 2 and discussed in this section. For completeness, three relevant insights from studying the results of runs associated with the Getting Ready level in earlier works are also included in the table.

Initial Onset: Hospital Unit Performance with Integrated COVID-19 Patient Care Paths

Finding 1. The hospital can serve up to 75% of its usual routine ED demand with half the number of ED beds and three-quarters the number of IGW beds retained for routine patients.

Creating isolation rooms from ED and IGW rooms for infected patients can enhance a hospital's capacity to serve COVID-19 patients while preserving its ability to care for routine emergency patients. The results predict that with 50% of the ED beds and 75% of IGW beds available to routine patients, the hospital can serve up to 75% of its routine emergency demand with the bottleneck in the IGW. However, usual ED excess capacity is depleted due to this diversion of beds to the COVID-19 response (Figure 1).

Finding 2 During the Initial Onset surge, a hospital may need to turn away emergency patients.

The simulation model replicates patient behaviors related to arriving, leaving without treatment (LWOT) due to long waits, waiting, and transfers. When hospitals reach their capacity for emergency or critical care, some patients will not receive treatment or standards of care must be lowered. To avoid turning away patients, hospitals may respond by placing patients in unconventional locations or even requiring two patients to share a single piece of equipment (e.g. ventilator) to cope with significant backups[20]. To study the need for external support and estimate the surge level at which rationing of care may be required, simulation features were added in five locations within the models to account for LWOT cases: at the entry to the ED, entry to the CDU, entry to the ICU by routine (non-COVID-19) emergency patients, entry to the ICU by COVID-19 patients, and entry to the isolation rooms.

Together, the daily average routine emergency and COVID-19 patients that cannot be served in the ICU can be as high as 67% ((8.2+4.9)/20)) of the ICU's total bed capacity (Figure 2). The model demonstrates that if the hospital continues to treat its usual daily 200 routine emergency patients of which five are admitted to the ICU, when COVID-19 patient account for

105 arrivals of which 11 are bound for the ICU, 82% of patients ((4.9+8.2)/16=0.82) would need alternative care. With such an estimate, hospitals can, in advance, repurpose space, modify operations, implement ASCs, prepare to collaborate with other health care facilities, or request external support (tents, personnel, and so forth), increasing the likelihood that all patients will receive treatment.

Finding 3. With 25 COVID-19 and 200 routine emergency patient arrivals daily, each ICU bed serves up to five patients per month – that number decreases to about 3.5 as the number of COVID-19 patient arrivals increases.

The number of patients per month that an ICU bed can serve is significantly higher with fewer COVID-19 patients due to the longer average LOS required of COVID-19 patients (median of between 4 and 21 days[21]) compared with that of routine patients (approximately 3 days on average for non-COVID-19 patients [22]). The difference is as high as 57% ((7.7-3.3)/3.3=0.57) for the test hospital. For routine times, for the typical daily arrival rate (200) of emergency patients, it is estimated that an ICU bed can serve up to nearly eight patients per month.

Outbreak: Implementing ASCs or Other Interventions for Added Capacity

Finding 4. Cancelling elective surgery frees up in-patient (IGW) beds, increasing capacity for treating routine emergency patients while simultaneously coping with the COVID-19 patient surge.

Results show that by redesigning the hospital to add a specialized care path for COVID-19 patients, the ED and larger hospital lose 30% (1107 to 770 weekly patient throughput) and 32% (1432 to 970 weekly patient throughput) capacity, respectively. To cope with periods of COVID-19 surge, hospitals have cancelled elective surgeries either by choice or mandate[23]. From run results, it is estimated that cancelling elective surgeries (75% of scheduled operations) enables the ED to serve 22% more patients (1148 instead of 970 weekly) and results in an 18% greater overall routine emergency patient throughput (943 instead of 770 weekly). It was also noted that more than half of the routine emergency patients (ESI level 2-5) who could not previously receive timely service (185 instead of 386 weekly) can be served as a consequence of the canceled surgeries.

Finding 5. Treatments that reduce COVID-19 patient intensive care LOS by one day increase a hospital's ICU capacity by 24%.

The most at-risk COVID-19 patients require ICU care. The simulation run results indicate that each one-day reduction in ICU LOS increases ICU patient throughput by between 9 and 24% (highest for the first day of reduction, with an overall average of 15%) in scenarios with usual emergency arrivals (200 daily arrivals of routine emergency patients) and high COVID-19 patient arrivals, i.e. 30 daily patient arrivals and higher. As expected, the greater the proportion of COVID-19 ICU patients, the greater the benefit of treatments that reduce average ICU LOS. Overall, for a wider range of 5-100 daily COVID-19 patient arrivals at a daily routine 200 emergency patients, the single-day reduction in ICU LOS average value ranged between 0.8-15%. A reduction in ICU LOS by 4-9 days enables up to double the throughput at a 100 COVID-19 average daily arrival rate.

Finding 6. A hospital's capacity for routine emergency and COVID-19 patients is highly dependent on the number of COVID-19 patients seeking care, as serving each COVID-19 patient requires, on average, more of the hospital's capacity (e.g. longer LOS in the ICU) than a single routine emergency patient.

Figure 3 demonstrates the impact on ICU capacity as the percent of COVID-19 patients increases even with a fixed total daily arrival of 200 routine emergency and COVID-19 patients. The results confirm that as the percentage of COVID-19 patients increases more resources are needed to serve the same number of emergency patients. Under routine conditions with no COVID-19 patients, the ICU bed utilization of the test hospital is 64% on average, but with 5% of the arrivals (10 patients per day) with COVID-19, the ICU averages 92% capacity. With 10% COVID-19 patient arrivals or, equivalently, 16% of admitted COVID-19 patients, the ICU bed utilization is 99%, a 35-percentage point increase above that of no COVID-19 patients. Isolation bed utilization (red line in Figure 3) simultaneously approaches 100% soon after the ICU reaches its maximum capacity.

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Hot Spot: Unified COVID-19 Care Increases Capacity

Finding 7. COVID-19 designated hospitals can serve up to five times the number of COVID-19 patients compared with a similar facility accepting mixed patients.

This increase is accomplished by: allowing ASCs and using all the available beds, nurses, and doctors ordinarily assigned to routine patients in the IGW, pre- and post-op units, and the ED for COVID-19 patient treatment. Increases of approximately 350% and 140% in throughput were noted for the ICU and isolation rooms, respectively. This can only be improved further with additional space (i.e. beds). It is estimated that a threefold increase in the number of COVID-19 patients can be served without compromising standards of care. ASCs add nearly 38% improvement (Figure 4).

Switch Points

Finding 8. There are two key switch points when hospitals must introduce strategies for increasing capacity or dedicate all resources to COVID-19 treatment to meet COVID-19 patient surge. Without such action, it may become necessary to ration care. A hospital can prepare for action by predicting the timing of these points.

Two key switch points can aid a hospital in coping with increasing COVID-19 patient demand. The first uses ASCs, specifically increased patient-to-staff ratios and repurposing of nonmedical space, and the second designates nearly all medical space and staff for COVID-19 treatment. Implementing ASCs allows the test hospital to serve, on average, 30 COVID-19 patient arrivals per day (~10 additional patients or 33% increase based on ICU throughput).

Dedicating the hospital to COVID-19 patients along with ASCs allows the hospital to serve an average of 40 more COVID-19 patient arrivals per day in the isolation rooms (a 133% increase) and an average of 80 more in the ICU (a 400% increase) (Figure 5). With additional negative pressure rooms for isolation and critical care nurses, the designated hospital could serve even higher numbers.

These estimates can help a region forecast its total COVID-19 patient response capability. By taking actions at the switch points or in advance of these points, hospitals will be prepared to meet increased COVID-19 patient arrivals at the onset of a surge and recognize tipping points where outside help or a hospital's complete dedication to COVID-19 would become essential. Anticipating switch points as surge demand diminishes can also aid in efficiently restarting routine services that were canceled during the surge.

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4. Limitations

The team is currently working with a significant hospital system to fully validate the COVID-19 model extensions against real-world data, a process that is expected to take another year or two, and is complicated by inconsistencies in data collection procedures over the course of the pandemic.

The models are U.S.-centric. Modifications to hospital layouts, workflows and other details may be required to replicate operations in other countries. They were also created generically, with the aim of capturing the most important features of COVID-19 patient care. Additional details may be desired to model specific hospitals, proposals for restructuring and alternative settings to those used herein.

5. Discussion

Meeting the challenges of surge demand on hospitals is crucial for regional, national, and international COVID-19 response efforts. Hospital administrators and regional directors are faced with decisions whose implications depend on hospital functionality. Each hospital is a complex, dynamically changing, constrained system with interconnected work flows and users (patients) with unique needs and care paths. As hospitals in a region form an interacting, complex, dynamic priority system, it is difficult to predict the impact of any decision on hospital or regional health care performance. State-of-the-art computer simulation modeling as proposed herein can aid decision makers in meeting these challenges and avoiding circumstances where a patient in need of care is unable to find it. It also facilitates the study of individual strategies whose benefits would be difficult to isolate in reality due to confounding effects of simultaneous actions and changing circumstances.

The authors are extending the modeling capabilities developed herein to assess regional hospital capacity for coping with COVID-19 or other pandemics under varying collaboration strategies extending prior hospital coalition work[9]. Other extensions might include study of: (1) the potential impacts of changing strategies on special patient populations by segmenting the routine patient stream into multiple classes; (2) the effects of limited PPE by restricting the PPE resource and requiring its use whenever a staff member is assigned to a patient (currently modeled, but with infinite PPE supplies); and (3) nurse, doctor or technician absenteeism, the probability of which might increase with increasing number of patient contacts and/or limited PPE availability, or decrease when suggested interventions are taken.

6. Conclusions

This paper fills several critical gaps in the literature for assessing the utility of possible hospital preparedness and response actions to the COVID-19 pandemic. Other works have studied hospital operations for more general applications [6]. These works focus primarily on one hospital function (e.g. operations [24]) or a single hospital unit (e.g. laboratory [25]; ED [26,27,28]; radiology [29]; OR [30]; ICU [31]). The authors are not aware of any works in the literature that take a similar whole-hospital approach. With few exceptions [7,8,9], prior works have not taken patient-based and resource-constrained perspectives. A couple of works consider emergency situations. For example, Yi et al.[32] used simulation and a regression model for capacity planning of hospitals under earthquake or other hazard events. Hospital capacity is presumed to be sufficient for any event.

Five specific interventions and two critical shifts in care strategies were identified that can potentially significantly increase hospital capacity for routine emergency and COVID-19 patients during a pandemic. Estimates and considerations presented in this paper inform hospitals in repurposing space, modifying operations, implementing crisis standards of care, and requesting external support, thus, increasing the likelihood that arriving patients, both routine emergency and pandemic, can be served. This type of predictive modeling can be critical to assist with planning for future epidemics.

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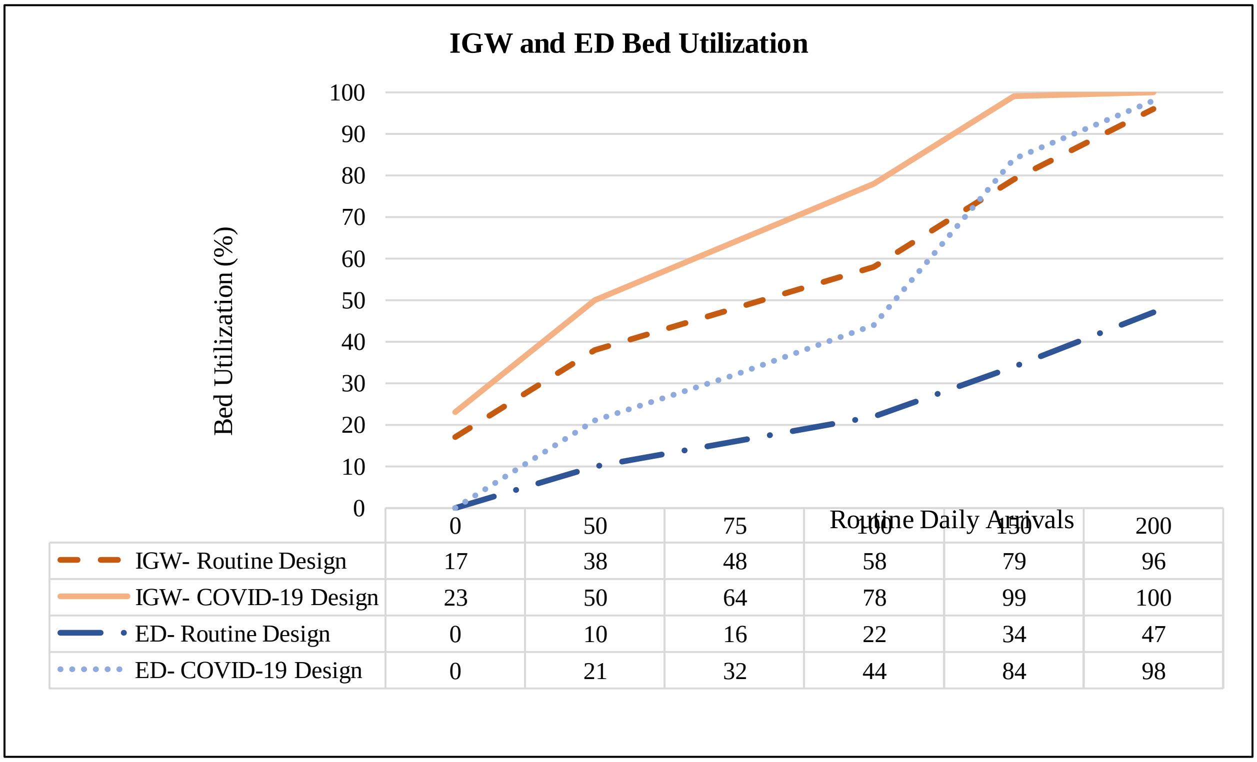
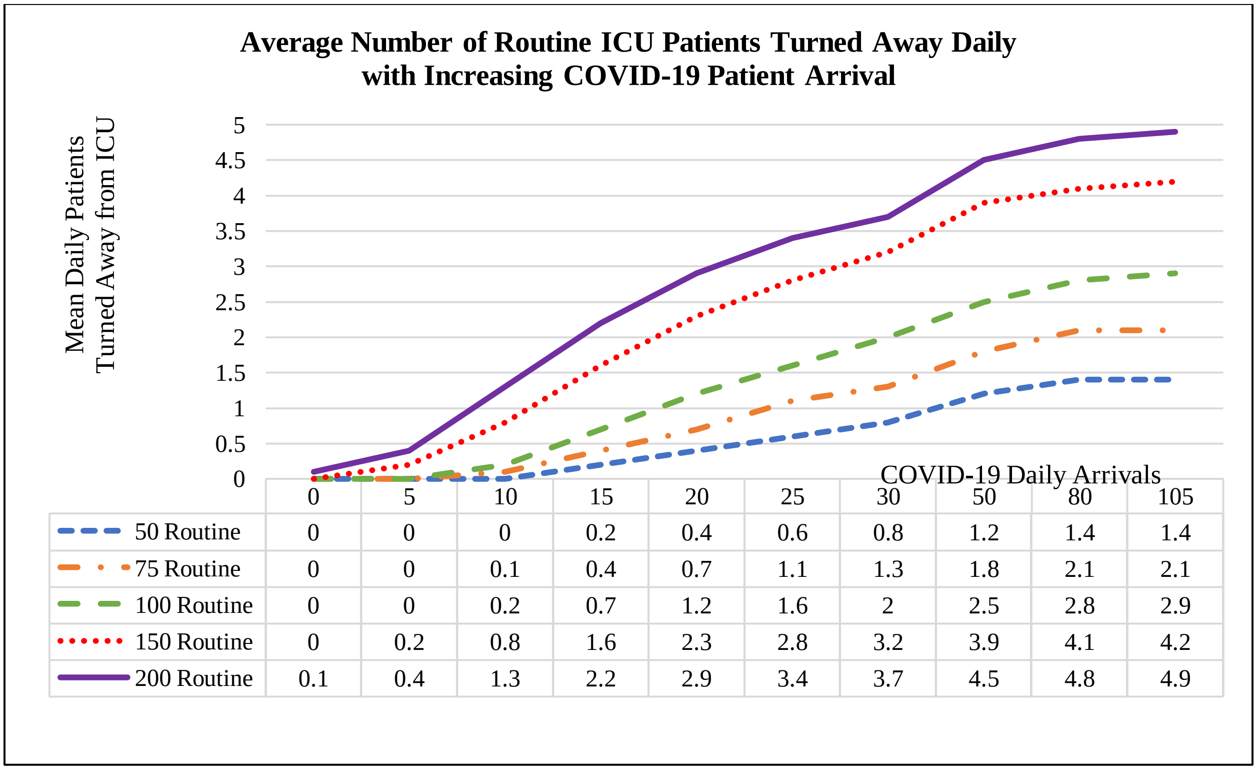
FIGURE LEGENDS



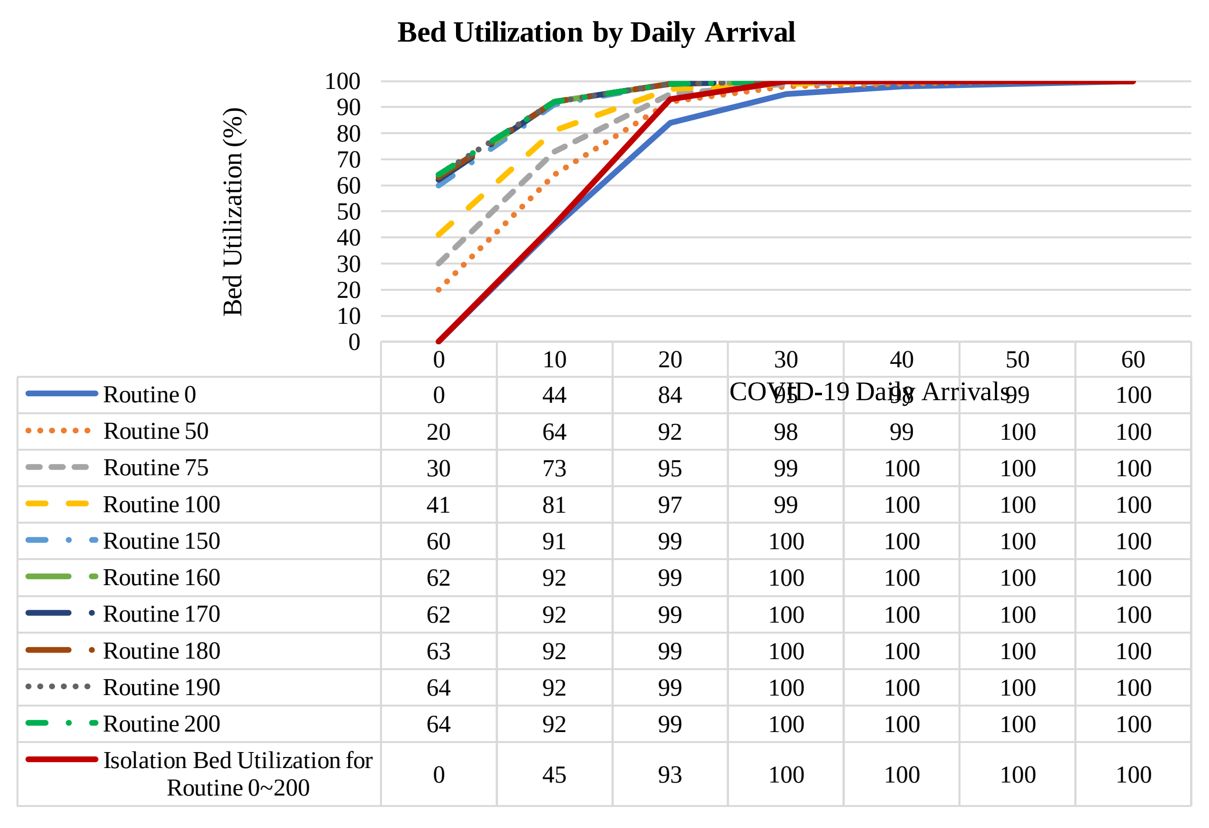
	0	50	75	100	150	200
IGW- Routine Design	17	38	48	58	79	96
IGW- COVID-19 Design	23	50	64	78	99	100
ED- Routine Design	0	10	16	22	34	47
ED- COVID-19 Design	0	21	32	44	84	98

Figure 1- Impact of Redesigning Hospitals on Routine Emergency Patients: IGW and ED Bed Utilization



	0	5	10	15	20	25	30	50	80	105
50 Routine	0	0	0	0.2	0.4	0.6	0.8	1.2	1.4	1.4
75 Routine	0	0	0.1	0.4	0.7	1.1	1.3	1.8	2.1	2.1
100 Routine	0	0	0.2	0.7	1.2	1.6	2	2.5	2.8	2.9
150 Routine	0	0.2	0.8	1.6	2.3	2.8	3.2	3.9	4.1	4.2
200 Routine	0.1	0.4	1.3	2.2	2.9	3.4	3.7	4.5	4.8	4.9

Figure 2- Impacts of Increased Daily Arrivals of COVID-19 Patients on Routine Patients Turned away from the ICU for Lack of Capacity



	0	10	20	30	40	50	60
Routine 0	0	44	84	95	98	99	100
Routine 50	20	64	92	98	99	100	100
Routine 75	30	73	95	99	100	100	100
Routine 100	41	81	97	99	100	100	100
Routine 150	60	91	99	100	100	100	100
Routine 160	62	92	99	100	100	100	100
Routine 170	62	92	99	100	100	100	100
Routine 180	63	92	99	100	100	100	100
Routine 190	64	92	99	100	100	100	100
Routine 200	64	92	99	100	100	100	100
Isolation Bed Utilization for Routine 0~200	0	45	93	100	100	100	100

Figure 3- ICU and Isolation Bed Utilization by COVID-19 and Routine Emergency Patient Arrival Combinations

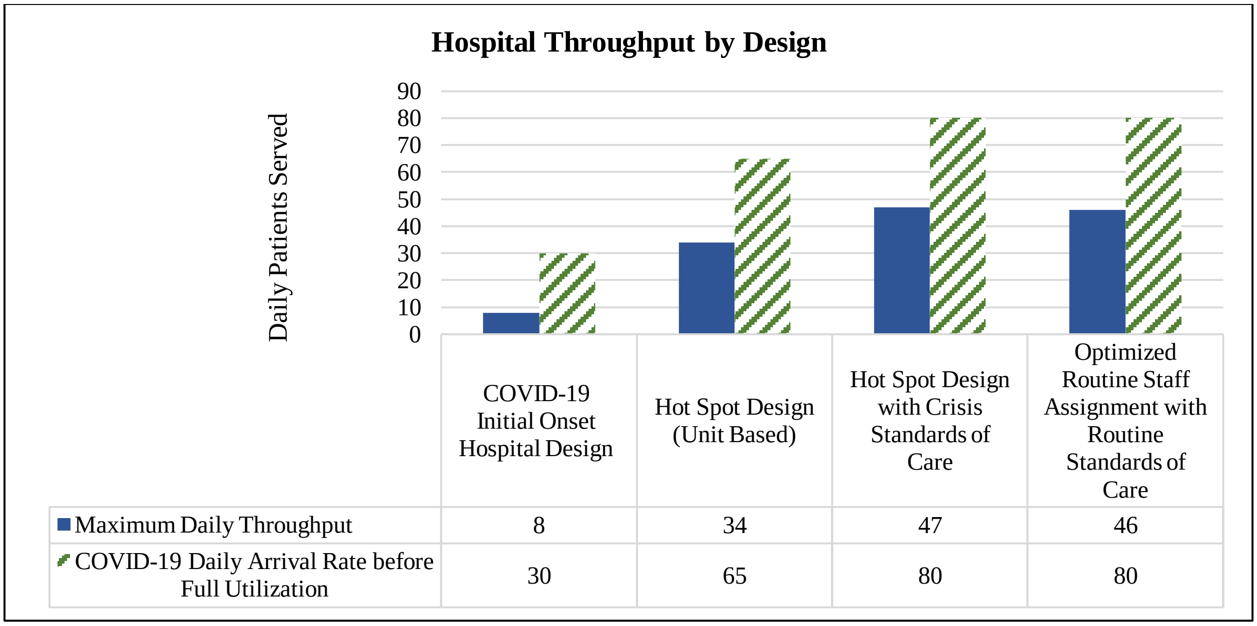
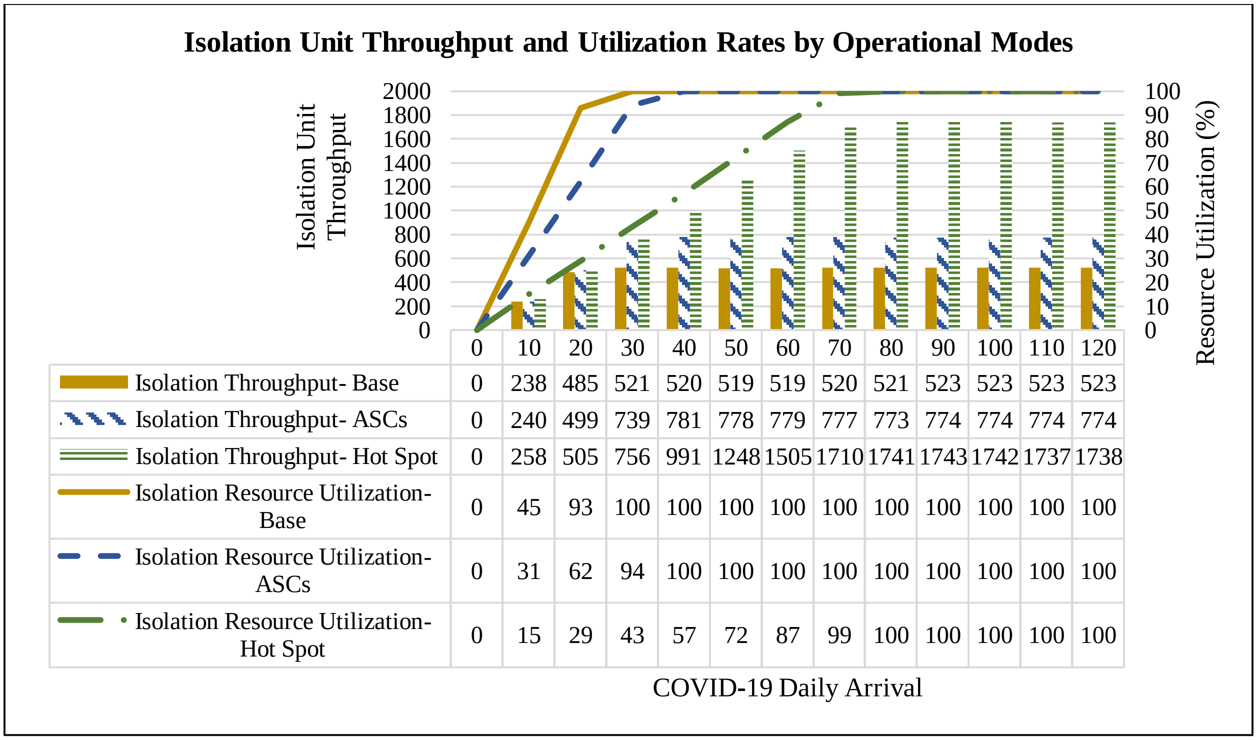
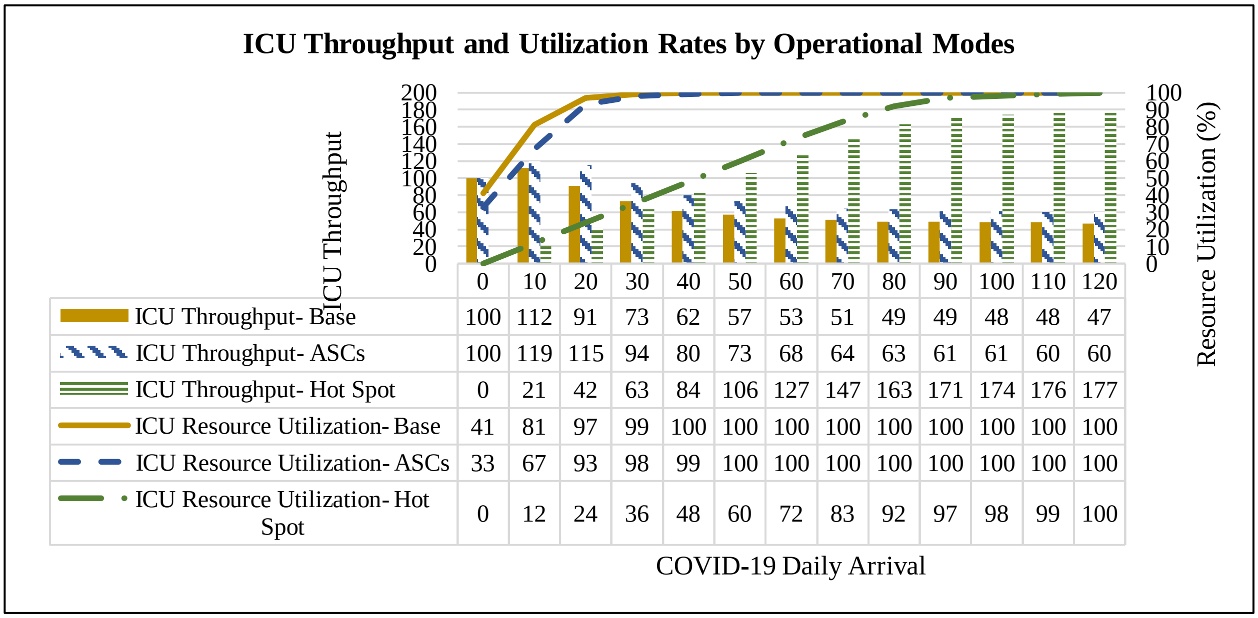


Figure 4- Hot Spot Throughput



	0	10	20	30	40	50	60	70	80	90	100	110	120
Isolation Throughput- Base	0	238	485	521	520	519	519	520	521	523	523	523	523
Isolation Throughput- ASCs	0	240	499	739	781	778	779	777	773	774	774	774	774
Isolation Throughput- Hot Spot	0	258	505	756	991	1248	1505	1710	1741	1743	1742	1737	1738
Isolation Resource Utilization- Base	0	45	93	100	100	100	100	100	100	100	100	100	100
Isolation Resource Utilization- ASCs	0	31	62	94	100	100	100	100	100	100	100	100	100
Isolation Resource Utilization- Hot Spot	0	15	29	43	57	72	87	99	100	100	100	100	100

Figure 5a- Isolation Throughput



	0	10	20	30	40	50	60	70	80	90	100	110	120
ICU Throughput- Base	100	112	91	73	62	57	53	51	49	49	48	48	47
ICU Throughput- ASCs	100	119	115	94	80	73	68	64	63	61	61	60	60
ICU Throughput- Hot Spot	0	21	42	63	84	106	127	147	163	171	174	176	177
ICU Resource Utilization- Base	41	81	97	99	100	100	100	100	100	100	100	100	100
ICU Resource Utilization- ASCs	33	67	93	98	99	100	100	100	100	100	100	100	100
ICU Resource Utilization- Hot Spot	0	12	24	36	48	60	72	83	92	97	98	99	100

Figure 5b- ICU Throughput

Figure 5- Isolation and ICU Throughput

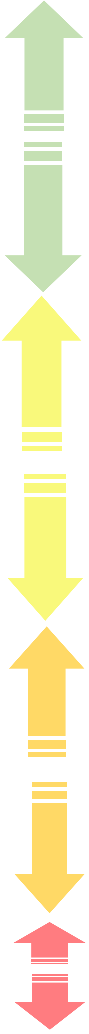
Table 1- COVID-19 Modeling Details

	Active Units	LOS Distribution by Units	Routine emergency Arrival Distribution (minutes)	COVID-19 Arrival Distribution (minutes)	Applied ASCs	Scenario Run Combination	Total Number of Scenario Runs
Getting Ready	10 initial critical units	**In ICU** Triangular (a=0.25, b=2, c=6 days)	Exponential (Mean: 7.2 200 Daily)	None	None		**30,750 Scenario Runs**
Initial Onset	10 initial critical units + CDU, Isolation Rooms	Parameters specific to COVID-19 care path **In ICU** Triangular (a=5, b=14, c=9 days) **In Isolation Rooms** Triangular (a=2, b=10, c=5 days) **In CDU** Constant (4 hours)	Exponential (Mean: 7.2 to 28.8 50 to 200 Daily)	Exponential (Mean: 13.71 to ∞ 0 to 105 Daily)	None	Finding 1: 1,500 runs Findings 2,3: 12,500 runs	

Outbreak	10 initial critical units + CDU, Isolation Rooms	Same as Initial Onset	Exponential (Mean: 7.2 to 28.8 50 to 200 Daily)	Exponential (Mean: 13.71 to ∞ 0 to 105 Daily)	*Combinations of:* Canceling elective surgeries Other interventions: Decreasing LOS for critical patients in ICU through increased patient to doctor ratio Increasing doctor- and nurse-to-patient ratios Opening nonmedical space	Finding 4: 250 runs Finding 5: 12,000 runs Finding 6: 1,000 runs
Hot Spot	OR, ICU, Lab and Imaging, Triage + CDU, Isolation Rooms	Same as Initial Onset	None	Exponential (Mean: 4.8 to ∞ 0 to 300 Daily)	Banning routine patient arrivals Increasing doctor- and nurse-to-patient ratios Repurposing space and personnel	Finding 7: 750 runs

Switch Point	Combination of Initial Onset and Hot Spot	Same as Initial Onset	Exponential (Mean: 14.4 to ∞ 0 to 100 Daily)	Exponential (Mean: 12 to ∞ 0 to 120 Daily)	*ASCs:* Increasing doctor- and nurse-to-patient ratios Opening nonmedical space (50% more IGW and isolation beds, 25% more ICU beds) *Hot Spot additions:* all applicable settings from Hot Spot	Finding 8: 32,500

Table 2-Summary of Findings (Initial Onset through Switch Point findings from this work)



Getting Ready	When combining options for modifying operations or reducing standards of care to meet a surge in demand, a super-additive impact can be obtained (8)
	The longest wait times were not necessarily found at bottleneck locations, but rather at the entry to downstream services (7)
	Forming a coalition and implementing capacity enhancement strategies in individual hospitals suffering from staff absenteeism due to a pandemic can aid the collaboration in serving more total patients (9)
Initial Onset	With only 50% ED and 75% IGW bed capacity for routine patients, resulting from accommodating COVID-19 patient care paths, only 75% of routine emergency patients can be served at usual daily arrival rates.
	The number of patients that cannot be served by the ICU increases with increasing COVID-19 patient arrivals at an unmet demand rate as high as 67% of the ICU's total bed capacity.
	Each ICU bed serves up to five patients per month. That number decreases to about 3.5 as the number of daily COVID-19 patients reaches the hospital's capacity.
Outbreak	Cancelling elective surgery frees up in-patient beds, increasing capacity for routine emergency patients from whom resources were diverted to meet the COVID-19 patient surge.
	Each day of reduction in ICU length of stay (LOS) increases ICU patient throughput by up to 24% for high levels of COVID-19 daily patient arrivals.
	Serving each COVID-19 patient requires more of the hospital's capacity than is needed to serve a single routine emergency patient.
Hot Spot	Repurposing of space and efficient reallocation of doctor and nurse resources can create a 500% increase in the number of COVID-19 patients served under crisis standards of care.
Switch Point	Two key switch points can aid a hospital in coping with increasing COVID-19 patient demand, the first of which uses ASCs and the second designates nearly all medical space and staff for COVID-19 treatment.