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ROBUST RESERVE CAPACITY PLANNING FOR POST-DISASTER HEALTH-CARE FACILITIES THROUGH INTELLIGENT PLANNING UNITS (IPUS)

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Abstract: Disasters often challenge the operation of health-care facilities. In particular, the insufficient supply of utility services and medical supplies can significantly compromise the operating capacities of hospitals without proper planning of reserve capacities (e.g., backup generators, bottled water, or a stockpile of emergency resources). This research employs the concept of intelligent planning units (IPUs) to guide health-care facilities on how to plan their reserve capacities in preparation for utility disruptions. The use of the IPUs enables resource planning at a single-patient care level based on the objective of a higher planning unit (e.g., service room level or hospital level). This research develops a mixed integer linear programming model that determines required reserve capacities for a post-disaster hospital to provide the highest level of care for patients (i.e., the objective of a high planning unit) through the optimization of the planning units for single-patient care within budget constraints. To demonstrate the implementation of the model, this study shows how to optimize the reserve capacities of a hypothetical hospital to operate intensive care unit services in two post-disaster scenarios: disruptions of water and power service. The recommended capacity plan based on the optimization model varies depending on a hospital's budget constraints for planning and target quality of service; the higher the risk awareness and target level of medical services, the more expensive the recommended plan. As such, this model can help hospitals adjust and allocate budgets for mitigation planning depending on their desired level of resilience.

1 INTRODUCTION

Health-care infrastructure is important for a community's well-being and, in addition to other types of infrastructure, provides services essential for people's social and economic activities (Deshmukh et al. 2011; Khanmohammadi et al. 2018). A hospital is often considered the most critical health-care facility since hospitals provide communities with direct access to medicine and medical care. Hospitals become more important in the aftermath of a disaster event because they are expected to remain operational and effective enough to treat injured patients in a timely manner (Arboleda et al. 2009). However, disasters often challenge hospital operations by disrupting the infrastructure services that are required to run the facilities and causing a surge in demand for health-care services (Choi and Hastak 2017). Consequently, post-disaster hospitals often fail to accommodate patients in medical need with timely and quality care. To be more specific, the disruption of utility services (i.e., water and electricity) may result in the loss of a hospital's critical operations and functions (e.g., imaging, surgery, ventilation, etc.) that are heavily dependent on the utilities if the hospital does not have proper contingency plans (Vugrin et al. 2015). Even if hospitals manage to maintain functionality during post-disaster recovery, a reduction in the serviceability of municipal utilities can compromise their treatment capacities, which often results in extended patient waiting time (Choi and Hastak 2017). The failure of hospitals to provide patients with medical services in a timely manner can compromise patient health conditions and ultimately threaten public health (Cochran and Roche 2009).

Considering this important role, hospitals should maintain their critical functions and operations at an acceptable level during post-disaster recovery. However, hospitals are not isolated and instead rely on other critical infrastructure (e.g., utility service providers) to operate their services (Arboleda et al. 2009; Choi and Hastak 2017). That is, the provision of services from such supporting infrastructure is essential to hospital operations. The interdependent nature of hospitals makes them particularly vulnerable to the cascading impacts of a disaster. (For example, the disruption of the power supply system by a disaster will affect the operations of a hospital). In an effort to minimize the risk of supporting infrastructure failure, hospitals need to prepare themselves through reserve capacity planning for emergencies. In fact, hospitals are required by the Joint Commission to have sufficient capacities to self-sustain their operations after disruptive events for at least 96 hours without any external support (Joint Commission 2009). Although the Joint Commission has a specific requirement about the duration of a hospital's self-sustainability, it does not stipulate the level of operation a hospital must maintain during a disruption. Furthermore, considering the nature of a disaster as a high impact, low-probability event, the planning of such auxiliary resources for utility disruption (e.g., bottled water for water disruptions and backup generators and diesel fuel for power disruptions) often requires substantial investment and thus readily becomes financially infeasible without systematic approaches (Choi and Hastak 2018). Thus, the identification of extra capacity needs has been an important research topic in the area of hospital resilience.

To effectively guide hospitals in planning reserve capacities, some researchers have developed new metrics to quantify hospital resilience (Cimellaro et al. 2010; Choi et al. 2019), simulated post-disaster scenarios to evaluate the effectiveness of capacity building options (Choi et al. 2019), and developed optimization models to minimize the cost of capacity building options in relation to plans for improvement (Vugrin et al. 2015). For example, Choi et al. (2019) proposed using the stress and strain of a health-care system to quantitatively measure the resilience of a hospital to an earthquake event. Further, they developed a system dynamic model to compare the effectiveness of alternative capacity building options in simulated post-earthquake scenarios.

Meanwhile, hospital resources become more limited in a post-disaster situation due to high recovery demand and possible disruption of supporting infrastructure (Deshmukh et al. 2011; Tariverdi et al. 2019). In this context, other researchers have emphasized the significance of a hospital's adaptive capacities in order to augment the effectiveness of the use of reserve capacities during disruption (Arboleda et al. 2007; Choi and Hastak 2018; Tariverdi et al. 2019; Vugrin et al. 2015). Specifically, Arboleda et al. (2008) considered medical teams' tendency to simplify treatment processes and reduce individual patients' treatment time when facing a long line of patients waiting for treatment. Further, Vugrin et al. (2015) considered auxiliary resources (i.e., reserve capacities) to keep patients in a higher care level when primary resources are not sufficient and integrated the flexibility of the operation into reserve capacity planning. As such, some researchers have considered the context of a hospital's post-disaster treatment processes in the planning stage (Arboleda et al. 2008; Vugrin et al. 2015); however, such planning methods do not guide a hospital's treatment processes for patients during recovery from a disaster. Taking the planning model of Vugrin et al. (2015) as an example, it is clear that their approach considering a hospital's adaptive capacity can determine how much auxiliary resources a hospital needs to plan for, but such plans do not answer a variety of questions that are important to efficiently manage the hospital's limited resources when treating patients during an emergency. Some of these questions can be stated as follows: How many patients should be treated with primary resources versus auxiliary resources? What level of care should be given to all accepted patients? How many patients should be evacuated due to an unsustainable level of care, and under what conditions will this be the case?

Most existing approaches to capacity planning have failed to include the detailed information necessary to optimize the required resources and thus yield the most streamlined treatment process for a post-disaster hospital (Hastak and Koo 2017). To be more specific, the treatment process for individual patients entails multiple functions (e.g., respiratory ventilation, suction, sanitation, etc.) from different service departments (e.g., emergency room, intensive care units, operating room, etc.) which are in turn dependent on resources (e.g., water, electricity, medical staff). To address such complex environment, Choi and Hastak (2018) adopted the concept of intelligent planning units (IPUs) proposed by Hastak and Koo (2017) to develop a framework to optimize resource allocations to provide all patients with their highest available care level in ex ante utility disruption scenarios.

This paper aims to demonstrate the implementation of the framework for a hospital's reserve capacity planning proposed by Choi and Hastak (2018) using planning scenarios for a hypothetical hospital. Within this framework, we break down the post-disaster operation of a hospital into process units for single-patient care at a functional level (e.g., planning of respiratory ventilation, suction, and sanitation for single patients) that can be scaled up to plan the process at higher levels (e.g., a service-room and/or hospital level). After creating the planning framework, we developed a mixed integer linear programming model to optimize the process IPUs with the aim of providing the best available care for hospitalized patients within budget constraints in potential utility disruption scenarios. The resulting capacity plans from the optimization model are then discussed in the context of post-disaster operations, followed by the conclusions of this study.

2 INTELLIGENT PLANNING UNITS IN THE CONTEXT OF HOSPITAL RESILIENCE

A built environment is a system of systems that consists of multiple interrelated subsystems (Hastak and Koo 2017). Due to the breadth and depth of the system, its management and planning readily becomes a challenge. Meanwhile, the system is also composed of subsystem components scalable (Figure 1a) from a basic component level (e.g., a building-block level) to higher-scale levels (e.g., room, building, and city levels). Acknowledging such fragmented nature, Hastak and Koo (2017) proposed the theory of IPUs that enables the planning of basic units in a built environment up to relevant higher levels to achieve the predefined goals of the system. With the application of emerging technologies such as the Internet of Things, Hastak and Koo's (2017) planning concept also accounts for the evolutionary nature of planning units during the life of the built environment since the planning units at a basic level are refining themselves through real-time communication based on collected data and predefined goals.

Health-care facilities also have similar operational and planning contexts, as observed in the planning of built environments (Figure 1b). For example, a hospital has multiple service rooms (e.g., intensive care units, an operating room, a laboratory, and an emergency room), each of which provides different medical services. Each service room has its own medical functions (e.g., auto/manual ventilation and vacuuming) to meet diverse patient needs. Choi and Hastak (2018) proposed the idea of using the IPU concept for health-care infrastructure planning in the context of disaster risk reduction. Following this concept, the framework for the process IPUs for a hospital's reserve capacity planning consists of three phases: IPU Planning, IPU Application, and IPU Networks. To facilitate the development of the framework, this study focuses on process IPUs that support servicing intensive care unit (ICU) patients during utility disruption.

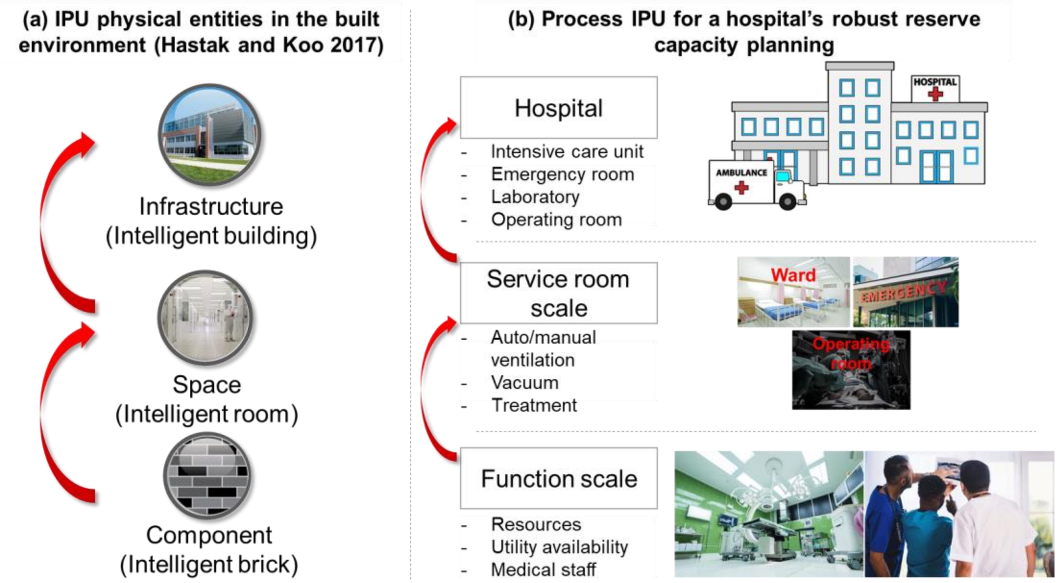


Figure 1: Application examples of intelligent planning units: (a) planning of built environments and (b) a hospital's reserve capacity planning (Adapted from Hastak and Koo 2017)

2.1 Phase 1: IPU Planning

In this study, the complex treatment processes of a hospital are broken into multiple process IPUs for single-patient care at a functional level (e.g., auto/manual ventilation, mechanical vacuuming/manual suction, and sanitation) as the lowest level that can be scaled up to higher levels of planning (e.g., the service-room level, hospital level, and hospital-network level) [Table 1]. The objective of the IPU at the highest level (i.e., a hospital-network level) is reflected in the IPUs at the lower levels (i.e., the functional level, service-room level, and hospital level). For example, a hospital network may aim to provide patients with the highest available level of care using its health-care network resources during an emergency. As one part of its preparedness planning, the hospital network may aim to develop an optimal evacuation protocol in case of emergency (Table 1). Meanwhile, individual hospitals may prepare their own emergency protocols to effectively operate their internal service departments with the aim of providing quality medical services, a process that requires optimal planning of service departments and their medical functions (i.e., IPU #A in Figure 2). IPUs must contain all the observable or controllable pieces of information required to achieve the defined goal. Following the IPU concept proposed by Choi and Hastak (2018), individual process IPUs for single-patient care at a functional level are defined with their own objectives and functions, and properties and specifications (Table 1). It is important to note that the objective of the same IPUs may vary depending on the life-cycle phase in disaster risk reduction. For example, process IPUs for single-patient care at an ICU level aims to provide the highest available level of service through adjustments of IPUs at a functional level under utility constraints (i.e., IPU #B in Figure 2).

Table 1: Intelligent Planning Unit Creation for a Hospital's Reserve Capacity Planning (Adapted from Choi and Hastak 2018)

IPU Scale	Key element for IPU planning	Description
Function	Objective & functions	Plan and optimize resources to perform functions in preparation for a disaster event
	Properties & specifications	Resource availability, utility availability (e.g., electricity and water), medical staff, backup generators, bottled water, etc.
Service room	Objective & functions	Optimize functions for individual patients in order to provide highest possible level of service in ex post disaster scenarios
	Properties & specifications	Functions (e.g., auto/manual ventilation, mechanical vacuuming/manual suction, and sanitation)
Hospital	Objective & functions	Make a plan or protocol to ensure the provision of the highest possible level of service across different service departments in ex post disaster scenarios
	Properties & specifications	Service rooms (e.g., intensive care unit, emergency room, laboratory, and operating room)
Hospital network	Objective & functions	Coordinate an evacuation or collaborative planning to ensure highest available level of service in case of emergency
	Properties & Specifications	Hospitals

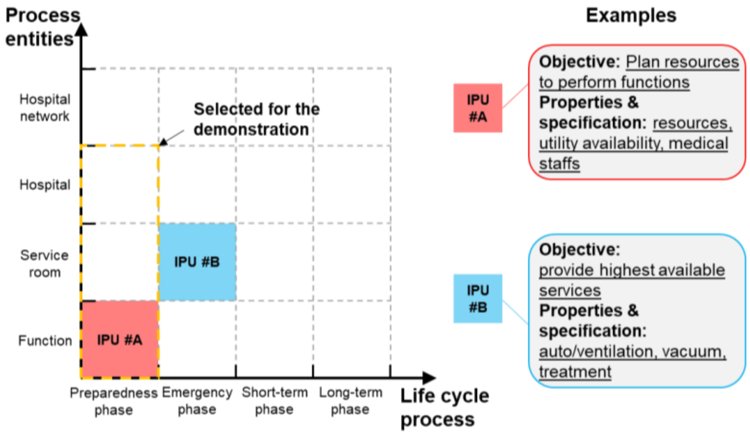


Figure 2: Matrix of the process intelligent planning units for hospital resilience (Adapted from Choi and Hastak 2018)

2.2 Phase 2: IPU Application

In this study, process IPUs for single-patient care are defined and implemented from a functional level up to a hospital level with the aim of providing the highest possible level of medical services for ICU patients in ex post disaster scenarios (Figure 2). Process IPUs at the functional level need to be replicated and integrated with proper adjustments in order to realize IPUs at higher levels (i.e., the service-room level and hospital level). For instance, a process IPU for planning the ICU department (i.e., at a service-room level) is defined and implemented by integrating its process IPUs for the ventilation, suction, and sanitation functions for single-patient care. Subsequently, the process IPU for single-patient care needs to be replicated to plan the functions required to operate the ICU department (i.e., for all the admitted ICU patients). Hastak and Koo (2017) named such an integrated IPU a composite IPU. Different service rooms may comprise the same or a similar set of functions for operations while also requiring different functionality levels (e.g., an operation room IPU may require ventilation, suction, and sanitation functions like the ICU but may require different levels of functionality).

2.3 Phase 3: IPU Networks

Process IPUs for single-patient care interact with others to refine treatment processes during an emergency. For example, if a hospital experiences a power outage for two days due to a disaster event, the IPUs for the ventilation function for single-patient care need to be adjusted in a way that maximizes its availability to patients depending on the availability of electricity (e.g., the capacity of backup generators and the amount of diesel fuel) and the number of medical staff. In this example, out of 20 ICU patients, 15 can be served with auto ventilation and 5 with manual ventilation. Accordingly, the process IPUs for the ventilation function share their status on serving patients (i.e., whether they are available or in use) and provide ventilation services based on the availability of resources. In the preparedness phase, such interactions between process IPUs at various levels are considered via ex ante analysis of disruptive events.

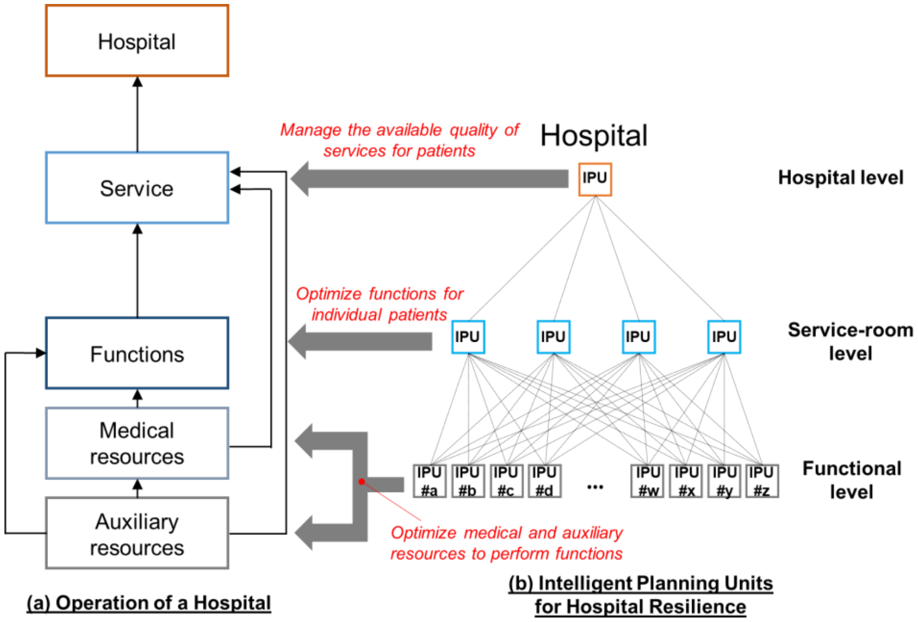
2.4 Development of the Optimization Model for Robust Reserve Capacity Planning

In a post-disaster scenario, a hospital likely experiences utility disruptions. To fulfill the hospital's mission (i.e., of providing the highest level of medical services possible for ICU patients), process IPUs at a functional level should be adjusted and optimized to treat individual patients in a way that delivers the highest level of care to the largest number of patients possible. Specifically, the IPU at the functional level (e.g., ventilation) will consider whether to choose the option that requires more utility services (e.g., auto ventilation) or less utility services (e.g., manual ventilation) depending on resource availability to fulfill its function (e.g., providing ventilation). Reflecting the objective of the process IPUs, the objective of the optimization model is set to minimize the cost associated with preparing medical resources and auxiliary resources to keep ICU patients at a high level of care within the given constraints on utility services (i.e., water and electricity). Please note that the patient care level is determined based on the availability of services. If patients receive services from all the required service rooms, they are experiencing the highest level of care. Otherwise, they are in a lower level of care. For example, ICU patients are required to receive not only ICU services but also services from an operating room and a laboratory, but the availability of these service rooms depends on the capacities of the process IPUs at their functional levels. For instance, suppose that the operating room requires a certain level of sanitation. If the required level of sanitation is not achievable for a certain number of ICU patients due to resource constraints, this excessive number of ICU patients cannot receive the operating room services, and their level of care is considered to be at a lower level than the optimum. The optimization model considers compromised levels of care for ICU patients through penalty functions.

$$\text{Min} \sum_{S} w_s \times \left(\sum_{t} \sum_{c} P_{c,t} \psi_c + \sum_{t} \sum_{k} R_{k,t} \lambda_k + \sum_{t} \sum_{m} AR_{m,t} h_m \right)$$

where w_s represents the weight of utility disruption scenario (s, $\sum_S w_s = 1$) and $P_{c,t}$ is the number of patients receiving a level of care c at time t. λ_k and h_m are the unit costs of medical resource (R_k) and auxiliary resource (AR_m), respectively.

Although the objective function of the proposed optimization model only represents the limited information available about the operations of a hospital, it should reflect the hierarchical operations of a hospital as shown in Figure 3a. As suggested by Vugrin et al. (2015), a hospital can provide patients with as high a level of services as the medical functions that are available (i.e., based on the service departments that are available and the number of ICU patients). Medical functions (e.g., how many patients need to use manual vs. auto ventilation in the case of the ventilation function) depend on the availability of medical resources (e.g., medical staff, ventilators, air delivery, backup generators, municipal utility lines [e.g., water and electricity]) and auxiliary resources (e.g., bottled water, generator fuel, bulk oxygen, bottled oxygen, etc.). The optimization model will determine the amount of medical and auxiliary resources to be used and the number of patients for each level of patient care based on the optimal value for functions and services. Such a hierarchical structure is well matched with the formation of IPUs from the functional level to the service-room level and hospital level (Figure 3b). As such, the optimized values for each entity (e.g., values for medical and auxiliary resources) in the hierarchy can be directly used as the optimized value for each IPU at the different levels (e.g., IPUs at the functional level).



(a) Operation of a Hospital

(b) Intelligent Planning Units for Hospital Resilience

Figure 3: Operational structure of a hospital and intelligent planning units for hospital resilience

3 RESERVE CAPACITY PLANNING OF A HYPOTHETICAL HOSPITAL FOR A DISASTER EVENT

Many researchers have studied how different disasters can affect utility disruptions and hospital operations and thus used this information to guide capacity building planning (Arboleda et al. 2007; Vugrin et al. 2015). In this hypothetical scenario, we consider utility disruptions (i.e., electricity and water disruption) as disaster impacts to determine the size of reserve capacities needed to meet the self-sustainability requirement. To solve the problem, this study develops a mixed integer linear programming model with the parameters, variables, and constraints shown in Table 2; the number of patients in each level of care (P_c) is a nonnegative integer and the other variables are treated as nonnegative values. In particular, although the medical demands of patients in the same department may vary depending on their health conditions, this model assumes the ICU patients' medical demands are homogeneous for the sake of simplicity and that ventilation functions are required in all departments. Also, as requested by the Joint Commission, this model assumes a 96-hour period for both the water and electricity disruption scenarios with 0.3 and 0.7 being used as the weight for the water and electricity disruption scenarios, respectively. In one disruption scenario (e.g., the water disruption scenario), the other utility service is assumed to be fully available to the hospital (e.g., the serviceability of electricity is 100% for the hospital). Disruption occurs at time $t = 2$ and lasts for four days (i.e., until $t = 5$). At time $t = 6$, 50% of pre-disaster serviceability is available, and it becomes fully available at time $t = 7$. The model also assumes \$100,000 as the budget constraint for reserve capacity planning (i.e., the cost of auxiliary and medical resources for a four-day disruption).

Table 2: Parameters and Variables of the Optimization Model

Patient Category	**Resources (R_k)**
ICU patient requiring ventilation	Ventilators ($k = 1$)
Patient Level of Care (c)	Air delivery ($k = 2$)
Nominal operations (ICU, operating room, and laboratory services available) [$c = 1$]	Medical staff ($k = 3$)
All services except elective surgery (ICU and laboratory services available) [$c = 2$]	Line power ($k = 4$)
An unsustainable state [$c = 3$]	Generator power ($k = 5$)
Service	Line water ($k = 6$)
ICU services (including ventilation)	**Auxiliary resources (AR_m)**
Operating room	Generator fuel ($m = 1$)
Laboratory	Bulk oxygen ($m = 2$)
Functions	Bottled oxygen ($m = 3$)
Auto ventilation	Air tanks ($m = 4$)
Manual ventilation	Bottled water ($m = 5$)
Mechanical vacuuming	Batteries for ventilators ($m = 6$)
Manual suction	**Disruption duration (W_s)**
Sanitation	Electricity: 4 days ($W_1 = 0.7$)
Time (t)	Water: 4 days ($W_2 = 0.3$)
Seven-day operation with one day as unit time	**Budget constraint for reserve capacity planning** \$100,000

In the scenario, a hospital can adapt its operations to given utility constraints in order to provide ICU patients with the possible highest care. For example, a hospital may use the manual ventilation option as a substitute to the auto ventilation option due to inadequate electricity, but such an adaptation would require more medical staff. The following entities have such supplementary relationships to support hospital operations within the utility constraints: auto ventilation and manual ventilation to fulfill the required ventilation function, mechanical vacuuming and manual suction to fulfill the required suction function, line water and bottled water to meet the water requirement, line power and backup generators with diesel fuel to meet the electricity requirement, and bulk oxygen and bottled oxygen to meet the air supply requirement. If a hospital cannot meet the required function and thus maintain a service room even after such adaptation processes, the service is not available to the patients and thus is treated as a penalty during the optimization process.

Figure 4 shows the optimized number of patients being treated with each level of care under the given constraints. In both the water and electricity disruption scenarios, the disruptive event occurs at time $t = 2$. If ICU patients can receive all services (e.g., ICU, operating room, and laboratory), they are considered to be receiving the highest level of care or Care Level 1($c = 1$). If they cannot receive the operating room service, they are considered to be receiving a lower level of care or Care Level 2 ($c = 2$). If patients are receiving an even lower level of care or Care Level 3 ($c = 3$), the hospital cannot provide an acceptable level of treatment; therefore, patients at Care Level 3 need to be evacuated.

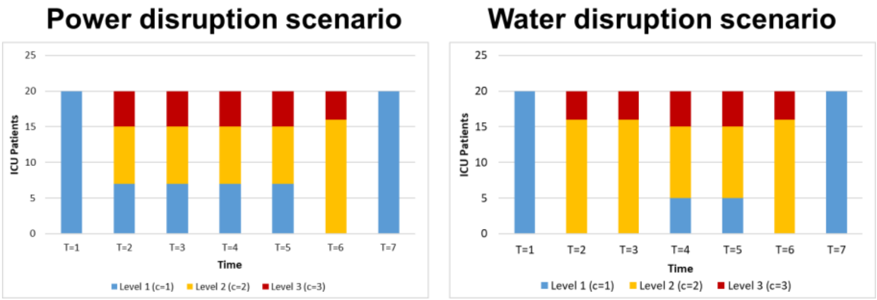


Figure 4: Optimized process intelligent planning units at a hospital level under the budget constraint of $100,000

As shown in Figure 4, the proposed optimization model can determine how many patients should be treated with each level of care under different disruption scenarios (i.e., by optimizing the process IPUs at a hospital level). The process IPUs at the hospital level are optimized through modification of the process IPU at the lower levels (e.g., the service-room level and functional level). For example, in the power disruption scenario, the process IPUs for the ventilation function for an ICU are optimized to use auto ventilation to meet demand equivalent to 11.64 patients and manual ventilation to meet demand equivalent to 3.35 patients (Figure 5a). Due to the insufficient auxiliary and medical resources, the ventilation function for the ICU can only serve 15 out of 20 ICU patients. The process IPUs of the ventilation function can be optimized for different service rooms (i.e., as seen in Figures 5a and 5c) in different disruption scenarios (i.e., as seen Figures 5b and 5d for the water disruption scenario).

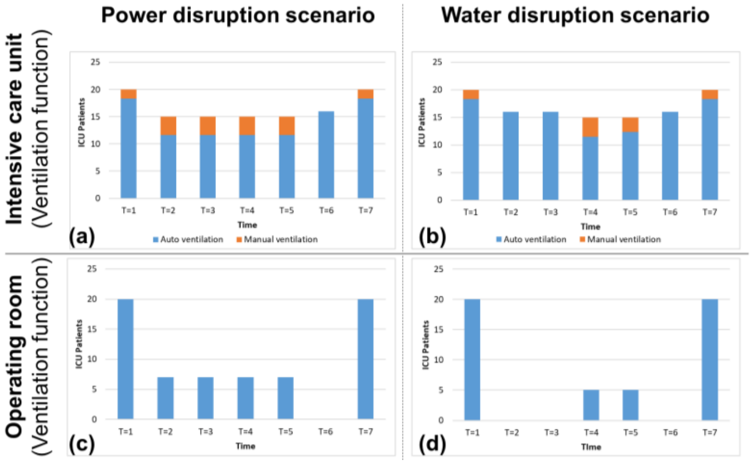


Figure 5: Optimized process intelligent planning units for the ventilation function for an intensive care unit and an operating room

4 DISCUSSIONS

In the hypothetical scenario, the global optimal solution for process IPUs was found (i.e., by optimizing the amount of medical and auxiliary resources), but the results show that some ICU patients will not receive at an acceptable level of care (i.e., by being categorized in Care Level 3 [*c* = 3]) with the current budget constraint of $100,000. If the resulting level of hospital resilience is not acceptable, decision makers can consider relaxing the budget constraint (i.e., increasing the budget) to achieve overall higher levels of care for ICU patients. Figure 6 shows the results of the optimizations with different budget constraints. As shown in Figure 6, the more the budget increases, the higher level of care all patients are likely to receive. That is, in the scenario with a budget of $100,000, 82.56% and 84.29% of ICU patients receive at least acceptable levels of care (i.e., Care Levels 1 and 2) in the power disruption scenario and water disruption scenario, respectively. In the scenario with a budget of $120,000, these percentages are improved to 93.57% and 95.00% while they rise up to 100.00% and 98.57% in the scenario with a budget of $130,000. As such, with the decision makers' input, the proposed framework can help a hospital to achieve the desired level of resilience within its feasible range of budgets.

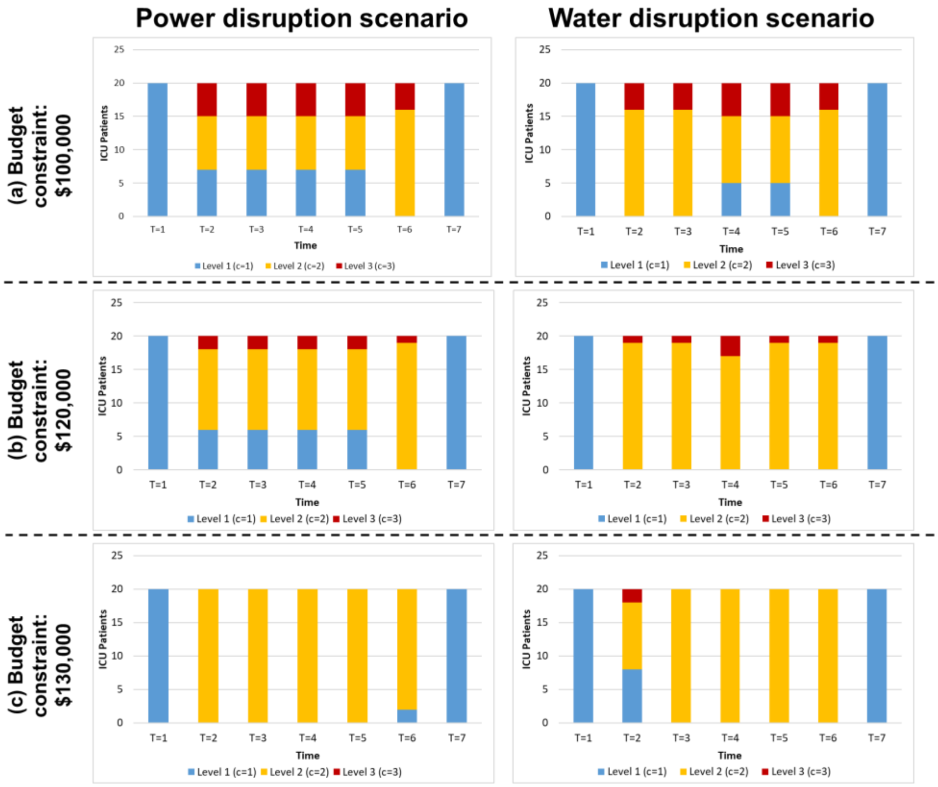


Figure 6: Process intelligent planning units at the hospital level under various budget constraints

5 CONCLUSIONS

The effective operation of health-care facilities is essential to community resilience. A hospital's failure to meet a post-disaster community's demands may threaten public health and cause social and economic losses. As such, these vital facilities are required to have extra capacities to self-sustain their operations for a certain period in case of a disruptive event. However, such a requirement does not provide enough guidance to hospitals on how to make a robust reserve capacity plan for possible disruptive events. This study proposes a framework using IPUs to optimize the size of reserve capacities (i.e., by considering the amount of medical and auxiliary resources needed to operate during disruption). Within this framework, we break down the post-disaster operation of a hospital into process units for single-patient care at a functional level (e.g., planning of respiratory ventilation, suction, and sanitation for single patients) that can be scaled up to plan the process at higher levels (e.g., the service-room level and/or hospital level). To demonstrate the implementation of the framework, this study employed a mixed integer linear programming technique with a hypothetical planning scenario. The proposed model is capable of not only determining the optimal size of reserve capacities within selected budget constraints but also optimizing process IPUs from the functional level up to the service-room level and hospital level. Although the results of this study show the potential for improving the current practice of hospital reserve capacity planning in hypothetical scenarios, the study requires the collection of primary data from hospitals to validate its implementation in real-world disaster planning. Furthermore, this study simplified the complex, heterogeneous treatment process for individual patients in the planning stage. Ideally, such diversity should be reflected in a hospital's capacity planning and can be integrated into the optimization model during future research.

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