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Prioritizing Burn-Injured Patients During a Disaster

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The U.S. government has mandated that, in a catastrophic event, metropolitan areas need to be capable of caring for 50 burn-injured patients per million population. In New York City, this corresponds to 400 patients. There are currently 140 burn beds in the region, which can be surged up to 210. To care for additional patients, hospitals without burn centers will be used to stabilize patients until burn beds become available. In this work, we develop a new system for prioritizing patients for transfer to burn beds as they become available and demonstrate its superiority over several other triage methods. Based on data from previous burn catastrophes, we study the feasibility of being able to admit 400 patients to burn beds within the critical three- to five-day time frame. We find that this is unlikely and that the ability to do so is highly dependent on the type of event and the demographics of the patient population. This work has implications for how disaster plans in other metropolitan areas should be developed.

Key words: healthcare; disaster planning; triage
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1. Introduction

Following the terrorist attacks on September 11, 2001, the U.S. government initiated the development of disaster plans for resource allocation in a bioterrorism or other mass casualty event (AHRQ 2006). There are many important operational issues to be considered in catastrophic events. Supply chain management as well as facility location and staffing are important factors when determining how to dispense antibiotics and other countermeasures (Lee et al. 2009, Bravata et al. 2006). In the event of a nuclear attack, guidance is needed on whether people should evacuate or take shelter in place (Wein et al. 2010). For large events, a critical consideration is how to determine who gets priority for limited resources (Argon et al. 2008). In this work, we focus on disaster planning for burn victims.

Patients with severe burns require specialized care because of their susceptibility to infection and potential complications due to inhalation injury and/or shock. Specialized treatments, including skin-grafting surgeries and highly specialized wound care, are best delivered in burn centers and are important in increasing the likelihood of survival and reducing complications and adverse outcomes (Committee on Trauma 1999).

There have been a number of events in recent years that would qualify as "burn disasters." For instance, in 2003, 493 people were caught in a fire at a Rhode Island night club, and 215 of them required treatment at a hospital (Mahoney et al. 2005). During this event, the trauma floor of the Rhode Island Hospital was converted to a burn center to provide the necessary resources to care for the victims. Other burn disasters were due to terrorist attacks such as those in Bali in 2002 and 2005 and the Jakarta Marriott Hotel bombing in 2003 (Chim et al. 2007). In these events, some patients were transported to Australia and Singapore for treatment. In all of these burn disaster events, there were more burn victims than could be adequately treated by existing burn centers, and other measures were required to provide care for all the patients.

To prepare for the possibility of a burn disaster occurring in American cities, the Federal Health Resources and Services Administration has developed standards for metropolitan areas. These include a mandate to develop a plan to care for 50 burn-injured patients per million people, beyond which a national plan would be activated to transport patients to other locations. For most metropolitan areas such as New York City (NYC), this mandate exceeds the current burn center capacity. Hence, there is a need to develop a burn disaster plan for the triage, transportation, and other related issues involved in managing an overloaded situation. The plan must include "guidelines and other materials for the management and treatment of selected burn-injured patients for the first three to five days in non–burn centers in the event of a large chemical or explosive event" (Fund for Public Health in New York 2005, p. 3). The three- to five-day horizon is consistent with clinical guidelines for the surgical treatment of burn victims.

There are currently 71 burn beds in NYC, which is typically a sufficient number to care for the normal demands of burn-injured patients. During periods of very high demand, burn centers can provide "surge" capacity of about 50% over their normal capacity by treating patients in other units of the hospital using burn service personnel. There are an additional 69 burn center beds in the 60-mile radius surrounding NYC (including New Jersey and Connecticut), bringing the total surge bed capacity in the greater metropolitan area to 210. Based on 2000 U.S. census data, the federal mandate of 50 patients per million people corresponds to being able to care for 400 NYC patients (Yurt et al. 2008), which far exceeds the surge capacity of 210 beds.

Consequently, a task force of burn specialists, emergency medicine physicians, hospital administrators, and NYC officials was created to develop a burn disaster response plan (Yurt et al. 2008). To do this, they identified hospitals that do not have burn centers, but have agreed to assist in stabilizing burn-injured patients until they can be transferred to a burn center.

The main focus of the work presented in this paper was to develop a detailed triage plan for prioritizing burn-injured patients for transfer to burn beds to maximize the benefit gained across all patients from receiving specialized burn care. More specifically, the NYC Task Force asked us to identify methods for refining and improving the initial triage system presented in Yurt et al. (2008), which uses broad categories based on age and burn severity to classify patients. We propose a new triage algorithm that includes individual survivability estimates and incorporates patient length of stay (LOS) as well as specific comorbidities that have significant impact on the triage performance. Based on data from previous burn catastrophes, we demonstrate that this new algorithm results in significantly better performance than other candidate triage methodologies. We also consider the feasibility of the proposed disaster plan to provide care in burn units for the vast majority of the 400 burn victims mandated by the federal guidelines for NYC. Our analyses suggest that it is highly improbable that most burn-injured patients will be able to be transferred to burn beds within the prescribed three- to five-day stabilization period. This suggests that federal assistance may be necessary even when the total number of burn-injured patients is much smaller than the 50 per million population guideline. Although this work focuses on improving the initial plan for NYC as outlined in Yurt et al. (2008), it provides useful insights for the development of burn disaster plans in other cities.

The rest of this paper is organized as follows. Section 2 provides background on burn care and the initial disaster plan established in 2008 (Yurt et al. 2008). Section 3 presents our stochastic model and optimization framework. Because of the complexity of the problem, we develop a heuristic prioritization algorithm. In §4, we discuss how to translate our model into practice and how to include two additional key factors: LOS and comorbidities. In §5, we show that including these factors can improve triage performance, measured in expected number of additional survivors, by up to 15%. Section 6 considers the feasibility of caring for all 400 patients in tier 1 burn beds. We find that the ability to treat all burn-injured patients within the first three to five days is highly dependent on the type of event and the severity of the patients. Finally, we provide some concluding remarks in §7.

2. Background

Careful triage of patients in any disaster scenario is critical in effectively utilizing limited healthcare resources. It is particularly vital in a burn disaster due to the specific and nuanced care required by burn-injured patients.

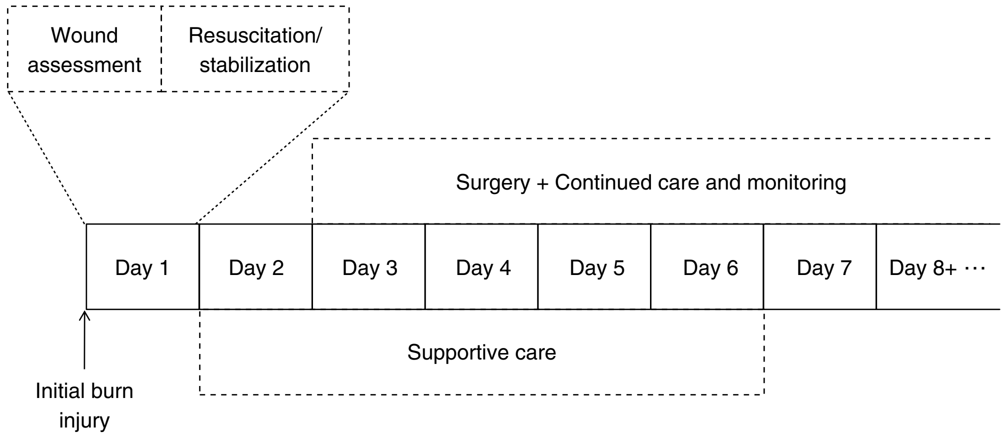
2.1. Burn Care

Figure 1 summarizes the typical treatment timeline for a burn-injured patient. During the first hours after injury, care for seriously injured burn patients focuses upon stabilization, resuscitation, and wound assessment. In the ensuing days, supportive care is continued, and, if possible, the patient is taken to the operating room for wound debridement and grafting as tolerated. It is recommended that such surgeries are performed by burn specialists. Although there is limited literature on the impact of delayed transfer to burn centers, it is widely accepted that it is not likely that there will be worse outcomes as long as patients are cared for by burn specialists within the first three to five days. Delayed treatment from burn specialists much longer than five days may result in worse outcomes if wounds are not properly cared for and begin to exhibit symptoms of infection and other clinical complications (Sheridan et al. 1999). Note that patients who suffer from extensive burn wounds may require multiple surgeries with recovery times between them because each skin graft covers a limited area.

2.2. Disaster Plan

The plan developed by the NYC Burn Disaster Task Force included a tiered system to triage and treat severely burned patients in hospitals with

Figure 1 **Timeline for Care of Burn-Injured Patients: From Wang (2010) and Private Communications**



and without burn centers as well as various other initiatives—such as communication protocols and competency-based training for emergency medical service (EMS) personnel and other staff at non–burn center hospitals (Leahy et al. 2012).

Facilities with New York (or New Jersey/Connecticut) State recognized burn centers are defined as tier 1 hospitals, hospitals with recognized trauma centers are defined as tier 2 hospitals, whereas hospitals with neither burn nor trauma designation are defined as tier 3 hospitals. Tier 3 hospitals are distinguished from all other non–burn center/non–trauma center hospitals in that they have agreed to participate in the plan and have accepted an emergency cache of burn wound care supplies and supplemental burn care training for emergency department and intensive care unit physicians and nurses in exchange for accepting up to 10 patients during a burn disaster scenario. Non–burn center/non–trauma center hospitals that opted out of plan participation could initially receive burn-injured patients who self-refer or are transported to these hospitals because of the availability of resources and/or proximity to the scene, but would then be transferred to participating hospitals.

Although some catastrophes may develop over the course of a few days, the Task Force was primarily concerned with disasters that create a sudden large surge in patient arrivals, such as those caused by a bombing or large fire. In such events, patients arrive at hospitals within a few hours, and certainly by the end of the first day. The timescale of patient arrivals is extremely short in relation to the average LOS of burn-injured patients, which is 13 days; hence, the Task Force focused on a reasonable worst-case scenario where all patients arrive at the beginning of the horizon.

As patients arrive at hospital emergency departments, they will be classified and given a triage score after examination. Based on these assessments, some patients will be transferred *into* tier 1 hospitals, whereas others may be transferred *out*, so as to reflect the prioritization scheme of the burn disaster plan. The Virtual Burn Consultation Center is a centralized tracking system that will be used to coordinate such interfacility transportation (Leahy et al. 2012).

Although the initial transportation and transfer logistics are part of the overall burn disaster plan developed by the Task Force, the major focus of the work described here was on the development of a triage algorithm to determine the prioritization of patients during the initial assessment and reassignment period, as well as for the transfer of patients who are provided their initial care in tier 2 and tier 3 hospitals, but who will be transferred to tier 1 hospitals as those beds become available. It is important to note that any triage algorithm is a decision aid that is meant to provide guidance to clinicians, who ultimately make the actual determination of patient priorities. However, given the number of relevant factors, an algorithm is necessary to deal with the complexity, and it is assumed that it will be followed in most cases.

The total surge capacity of tier 1 hospitals' burn beds in the greater metropolitan area is 210. If there are more than 210 burn-injured patients, tier 2 and tier 3 hospitals will be used to stabilize patients until they can be transferred into a tier 1 hospital, with preference given to tier 2 hospitals. Because burn-injured patients may require resuscitation, cardiopulmonary stabilization, and emergency care procedures prior to skin-grafting surgeries, the tier 2 and tier 3 hospitals were selected based on their ability to stabilize and provide the basic wound care required within the first few days. By day 3, most burn-injured patients should receive specialized burn care in a tier 1 hospital. Some patients are less delay sensitive and can wait up to five days to receive tier 1 care without incurring harm. If the total number of burn-injured patients is estimated to be beyond the number that can be admitted to treatment in a specialized burn bed by day 5, a national plan that would involve air transport to other metropolitan areas would go into effect. Because such a national plan would be very costly, complex, and potentially dangerous for many burn victims, the objective of the Task Force was to devise a plan that could provide for the treatment of up to 400 burn-injured patients in tier 1 facilities within three to five days.

There are three main factors that affect patient survivability and LOS: burn size (as measured by total body surface area (TBSA)), age, and inhalation injury (IHI). The triage decision matrix from Saffle et al. (2005) classifies patients based on likelihood of survival. Patients who are expected to survive and have good outcomes without requiring burn center admission are categorized as "outpatients"; "very high" patients who are treated in a burn center have a survival likelihood greater than or equal to 90% and require a length of stay between 14 and 21 days and one to two surgical procedures; "high" patients also have a high survival likelihood greater than or equal to 90% but require more aggressive care, with multiple surgeries and LOS greater than 21 days; "medium" patients have a survival likelihood of 50%–90% and require multiple surgeries and LOS of greater than 21 days; "low" patients have a survival likelihood of less than 50% even with aggressive treatment; "expectant" patients have a survival likelihood of less than 10%. LOS is defined as the duration of time in the burn unit until discharge.

This initial matrix was modified to include the presence of inhalation injury (Yurt et al. 2008). If the goal were simply to maximize the expected number of survivors, patients with the highest probability of survival would be favored for access to tier 1 burn beds. However, priority for tier 1 beds was determined under the premise that burn beds should first be given to patients who are severe enough that they will benefit significantly from specialized burn care, but not so severe that they are unlikely to survive even if provided with the prescribed treatment. Hence, the burn disaster triage matrix was based on the clinical judgment of burn treatment experts as to which patients would *benefit most* from specialized burn care. In this determination, the least injured patients were deemed to have a very high likelihood of survival, even if they were not admitted to a burn unit within the five-day horizon mentioned above, and so they were not included in the highest priority group. The modified decision matrix, shown in Figure 2, creates a block priority structure that was the starting point for the work described in this paper. A patient's *type* determines his priority for tier 1 beds. All patients categorized as outpatient are not considered in the burn disaster infrastructure. Type 1 patients (in gray) are given first priority for tier 1 beds. These patients consist of very high, high, and medium patients from Saffle et al. (2005) and were identified as the types of patients who are most likely to benefit from being treated in a burn center. All other patients (labeled with tier 2/3 in the matrix) have lower priority for transfer into tier 1 beds as they become available.

Figure 2 **Burn Disaster Receiving Hospital Triage Matrix, as Reported in Yurt et al. (2008)**

			0-10% + IHI	11-20% + IHI	21-30% + IHI	31-40% + IHI	41-50% + IHI	51-60% + IHI	51-70% + IHI	>71% + IHI
	Burn Size									
Age	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	90+
0-1	Tier 2/3	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3
2-4	Outpatient	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3	Tier 2/3
5-19	Outpatient	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3
20-29	Outpatient	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3
30-39	Outpatient	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3
40-49	Outpatient	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3	Tier 2/3
50-59	Outpatient	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3
60-69	Tier 2/3	Tier 2/3	Tier 1	Tier 1	Tier 1	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3
70+	Tier 2/3	Tier 2/3	Tier 1	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3	Tier 2/3

Tier 1 = Type 1 Tier 2/3 = Type 2A Tier 2/3 = Type 2B Tier 2/3 = Type 3

These patients can be stratified into two different types: type 2 patients (in lines) receive priority over type 3 patients (in dots). Type 2 patients can be further divided into two subtypes. The first type have a TBSA less than or equal to 20% and are labeled as very high in Saffle et al. (2005); the severity of their burn is limited enough that they are likely to survive even with delayed treatment in a tier 1 burn bed. We refer to these as type 2A patients. The second type are labeled as low in Saffle et al. (2005); their likelihood of survival is low enough that treatment in a tier 1 hospital is not as potentially beneficial as it is for tier 1 patients. We refer to these as type 2B patients. The last patient type consists of the expectant patients, who are only treated in a burn bed if there is availability because their survival is highly unlikely. We refer to these as type 3 patients.

This block triage plan was considered a good starting point, primarily because (1) it is based on data from the National Burn Repository as well as the clinical judgment of experienced burn clinicians and (2) it is simple and easy to implement. However, a major shortcoming of this triage system is that it is a gross categorization scheme with three priority types: types 1, 2, and 3. If there are more type 1 patients than there are tier 1 beds, there are no guidelines to determine which patients get priority. Similarly, as tier 1 beds become available, there are no guidelines to differentiate among the type 2 and type 3 patients. Finally, although this block plan is based on expert opinion on patients' expected increase in likelihood of survival due to treatment in a burn unit, it does not incorporate any individual estimates of survival either with or without specialized burn care. We discuss this issue in more detail in §4.

The goal of the work we were asked to perform by the NYC Task Force was to prioritize patients within these gross categories. In doing so, we decided to consider if and how to incorporate comorbidities in the triage plan, noting that comorbidities can significantly impact patient survivability and LOS. As we discuss in subsequent sections, we also examined the implicit assumptions of the original block matrix plan and the feasibility of providing burn unit treatment for all 400 burn victims within the designated time horizon.

2.3. Operations Literature

Patient triage, which is essentially a prioritization scheme, has generated substantial attention from the operations research community. Classical index rule results from the scheduling literature (see Pinedo 2008) can often provide insight into how to manage patient triage. The well-known c-μ rule minimizes holding costs in a variety of settings (Buyukkoc et al. 1985, van Mieghem 1995). Saghafian et al. (2011) modified this priority rule to incorporate a complexity measure for patient triage in the emergency department.

Patient triage in disaster scenarios has the additional complication that, because the number of patients exceeds the number of health resources (beds, nurses, physicians, etc.), some, or even many, patients may not be able to receive treatment before they die, corresponding to patient abandonment. Glazebrook et al. (2004) proposed a (c-μ)-like priority rule that maximizes reward as the exponential abandonment rates go to zero. A similar priority rule was proposed by Argon et al. (2008) for general service times and abandonment rates. What separates our work from these works is that we consider how to leverage the structure and timeline of the treatment of burn-injured patients in designing a triage system. In doing so, we emphasize the need to combine mathematical rigor with clinical relevance and judgment to encourage physician adoption.

One issue of great concern to the physicians is how to triage patients when their medical history is unknown. In a classification scheme based on patient severity, the presence or lack of comorbidities can have substantial impact on a patient's priority. Argon and Ziya (2009) proposed a triage scheme to minimize long-run average waiting costs under imperfect customer classification. Each patient was associated with a probability of being of higher priority and triage was done in decreasing order of this probability. Our work also considers uncertainty in patient classification; however, it may be possible to expend some effort, via tests or speaking to the patient, to extract information about the presence of a particular comorbidity. Certainly, it is time consuming and costly to extract information on *all* possible comorbidities. Hence, we determine which, if any, comorbidities are most important in assessing survival probabilities and/or length of stay. Finally, the objective of our triage system is quite different because our time horizon is finite given the criticality of treating burn-injured patients within the first three to five days following injury.

Our goal in this work is to bring a systematic framework to a current, important, and real-world problem. Triage plans, especially in disaster scenarios, are inherently *qualitative* because decisions have to be made quickly with limited data. The challenge is to bring mathematical rigor based on incomplete data to an inherently clinical and subjective decision process.

3. Model and a Heuristic

The goal of a disaster triage plan is to use the limited resources available so as to maximize the overall benefit to the affected population. Although in the case of burn patients, benefit can include improvements with respect to scarring and disability, the most important performance metric is clearly the increase in the likelihood of survival. Therefore, the ideal model for prioritizing patients to burn beds would be one that maximizes the overall increase in the expected number of survivors due to use of these beds. We describe such a model for the NYC burn disaster situation in this section. As we explain in more detail in a subsequent section, we must infer these benefits because of limitations in available data.

There are N patients who are eligible for treatment in one of the B tier 1 burn beds at the beginning of the horizon, where $B < N$. We assume that there is sufficient capacity in the tier 2/3 beds to accommodate all burn-injured patients not initially placed into a tier 1 bed while they wait to be transferred into a tier 1 burn bed.

We assume that we know all patients' probability of survival if they do not receive timely care in a tier 1 bed, as well as the increase in this probability if they do. We further assume that patients fall into one of two classes that defines their delay tolerance for burn unit care. Specifically, a class 1 patient must be transferred to a tier 1 bed within three days to realize the associated improvement in survivability, whereas a class 2 patient can remain in a tier 2/3 bed for up to five days before being transferred to a tier 1 bed without jeopardizing his probability of survival.

Each patient $i \in \{1, 2, \ldots, N\}$ is defined by his class, $C_i \in \{1, 2\}$, his increase in probability of survival due to timely tier 1 burn care, ΔP_i, and his expected LOS, L_i. Although we initially assume that patient i's LOS is exponentially distributed with mean L_i, we relax this assumption later.

Let t_i be the time at which patient i is transferred into one of the B beds at which time he generates reward

$$\Delta P_i[\mathbf{1}_{\{t_i \le 3,\, C_i=1\}} + \mathbf{1}_{\{t_i \le 5,\, C_i=2\}}].$$

That is, a class 1 patient who is transferred within his three-day delay tolerance will benefit ΔP_i from tier 1 burn care. Note that not all class 1 patients are necessarily type 1 patients. Likewise, a class 2 patient must be transferred within his five-day delay tolerance. Let $t_i(\pi)$ be the (random) time patient i is transferred into a tier 1 burn bed under triage policy π. Our objective is to select the triage algorithm, π, which maximizes the total expected increase in the number of survivors due to timely burn unit treatment.

$$\max_{\pi} E\left[\sum_{i=1}^{N} \Delta P_i[\mathbf{1}_{\{t_i(\pi) \le 3,\, C_i=1\}} + \mathbf{1}_{\{t_i(\pi) \le 5,\, C_i=2\}}]\right]. \quad (1)$$

3.1. Potential Triage Policies

If all patients had to *complete*, rather than *start*, treatment within the first five days, then a simple index rule that prioritizes patients in decreasing order of the ratio between patient benefit (i.e., increase in survivability) and expected LOS ($\Delta P_i/L_i$) (i.e., the incremental reward per day in the burn center) would be optimal. This can be shown via a simple interchange argument. Such an index rule leverages known results from the classical scheduling literature where *weighted shortest processing time* (*WSPT*) *first* is optimal for a number of parallel processing scheduling problems (see Pinedo 2008).

Our problem has a modified constraint that requires class 1 and class 2 patients to *begin* treatment within the first three and five days, respectively, to generate any reward. This makes our scheduling problem substantially more difficult. In particular, one can map our scheduling problem with objective (1) to a stochastic scheduling problem with an objective of minimizing the weighted number of tardy jobs, where the weight for job i is ΔP_i and the due date is $3 \cdot \mathbf{1}_{\{C_i=1\}} + 5 \cdot \mathbf{1}_{\{C_i=2\}} + S_i$, where S_i is the processing time for job i. Hence, the job must start processing by time $T = 3$ (or 5) days if he is class 1 (or 2). If patient LOS were deterministic, i.e., if $S_i = L_i$ with probability 1, this problem would be NP-hard (Pinedo 2008). The most commonly used heuristic for the deterministic problem is the WSPT index rule: $\Delta P_i/L_i$. However, in the worst case, the performance of this heuristic can be arbitrarily bad. In our stochastic model, the service times are independent exponential random variables, so the due dates are now random and correlated with the service times, adding additional complexity.

There are various results in the literature on minimizing expected weighted tardy jobs. More general models, for instance, with arbitrary deadlines or service times distribution, can be shown to be NP-hard. In special cases, optimal policies are known. For instance, with independent and identically distributed due dates and processing times, it is optimal to sequence jobs in order of weights (Boxma and Forst 1986). Forst (2010) identifies conditions for optimality, which in our case would correspond to the optimality of WPST if $\Delta P_i \ge \Delta P_j$ if and only if $L_i \le L_j$. Unfortunately, this condition is too restrictive for the burn triage problem, and so WSPT is not necessarily optimal. In other cases, such as Jang and Klein (2002), which examines a single machine with a common deterministic due date, heuristic algorithms must be considered.

3.2. Proposed Heuristic

Given the inherent difficulty of solving for the optimal triage algorithm, we focus on a modified version of the most commonly used heuristic, which is to prioritize patients in decreasing order of $\Delta P_i/L_i$. The average LOS of burn-injured patients is quite large (much more than five days), as seen in Table 4. Consequently, the distinction between *starting* versus *completing* treatment within the first three or five days is significant. Consider a simple example with two class 2 patients and one bed. Patient A has benefit potential 0.10 and expected LOS of 30 days. Patient B has benefit potential 0.05 and expected LOS of 10 days. Using the WSPT heuristic, patient B gets priority because $0.05/10$ is greater than $0.10/30$. With probability 0.3935, patient B completes before five days, and patient A can also start treatment within the first five days. Hence, the expected benefit, i.e., number of additional patients' lives saved, by scheduling patient B first is $0.0893 = 0.05 + 0.3935 \cdot 0.10$. On the other hand, the expected benefit by scheduling patient A first is $0.1077 = 0.10 + 0.1535 \cdot 0.05$. Because these patients both have very long LOS, the likelihood of being able to start treatment for the second patient is very low. Hence, it is better to start with the patient with the highest benefit potential (patient A).

Consider a more general example with two patients and one bed. Patients A and B have benefit potentials ΔP_A and ΔP_B, respectively; they are both class 1; their LOS, S_A and S_B, are exponentially distributed with mean L_A and L_B. We consider the criteria such that patient A should be given priority. That is, under what conditions is the expected benefit larger when patient A is given priority versus when patient B is given priority? This occurs when

$$\Delta P_A + \Delta P_B F_A(3) \geq \Delta P_B + \Delta P_A F_B(3)$$
$$\Leftrightarrow \quad \frac{\Delta P_A}{1 - F_A(3)} \geq \frac{\Delta P_B}{1 - F_B(3)}, \tag{2}$$

where $F_i(x) = P(S_i < x)$ is the cumulative distribution function of an exponential random variable with mean L_i. Hence, patient A should be given priority if his index, $\Delta P_A / P(S_A \geq 3)$, is larger than patient B's index, $\Delta P_B / P(S_B \geq 3)$. Based on this analysis, our proposed heuristic algorithm is to prioritize patients in decreasing order of the following triage index:

$$\frac{\Delta P_i}{P(S_i \geq 3)} = \Delta P_i e^{3/L_i}. \tag{3}$$

This new triage index would give priority to patient A in the example given above where WSPT gives priority to patient B. Hence, it has a higher expected benefit than WSPT. In general, the proposed algorithm is not optimal. Consider the following example with three patients and one bed. The patient parameters are summarized in Table 1. Patient A has the shortest expected LOS but also the lowest benefit potential. However, given the short horizon of three days, patient A has high priority. Based on the proposed triage algorithm in (3), patients should be prioritized in the order A, B, C. One can do some quick algebra to conclude that this ordering results in the expected benefit of 0.1146. If, instead, patients are prioritized in the order A, C, B, the expected benefit is 0.1147, which is marginally ($< 0.05\%$) higher than the proposed heuristic. Because the LOS are so large compared to the horizon of three days, the second patient is unlikely to finish before the end of the horizon, so it is better to schedule patient C, with the highest benefit potential, than patient B, which has a shorter LOS and lower benefit potential. Despite the suboptimality of the proposed heuristic, the magnitude of suboptimality in this example is very small, suggesting that this heuristic is likely to perform well in practice.

Table 1 Patient Parameters for Three-Patient, One-Bed Example

Patient	Class (C_i)	Benefit potential (ΔP_i)	Mean LOS (L_i)	Priority index ($\Delta P_i e^{3/L_i}$)
A	1	0.080	7	0.1228
B	1	0.090	15	0.1099
C	1	0.095	30	0.1050

One could potentially consider more sophisticated algorithms, such as varying the denominator based on patient class and time. For instance, the index in (3) could use the probability of completing within five days instead of three days: $\Delta P_i e^{5/L_i}$. Because the majority of patients are class 1, and so must start treatment within three days of a burn injury, this is unlikely to have a substantial impact on performance. Furthermore, we conducted simulation studies (using the simulation model described in Appendix A) and found there is no discernible difference between considering the five- or three-day limit given the long LOS of typical burn-injured patients. We note that when patient LOS is very long, the proposed index is primarily determined by the benefit ΔP_i. This is because the portion of the index that depends on LOS, e^{e/L_i}, is very flat for large L_i. Therefore, we expect the suboptimality to be small in such cases. Finally, our proposed triage index in (3) is relatively simple, which makes it ideal for real-world implementation.

A major challenge in actually using the proposed model and heuristic is the lack of appropriate data. Quantifying the benefit, ΔP_i, for each patient is not possible because there is no source of data on the likelihood of survival for burn patients not treated in a burn unit since almost all burn patients are transferred to burn units for care. The National Burn Repository only maintains outcome data for burn-injured patients who are treated in burn units. In the next section, we describe several approaches for dealing with this data limitation.

4. Parameter Estimation and Model Refinement

4.1. Parameter Estimation

We now consider how to estimate the parameters for our proposed algorithm for use in the burn disaster plan. In particular, we need to determine the benefit, expected LOS, and class (ΔP_i, L_i, and C_i) for each patient i.

4.1.1. Survival Probability. We begin with the likelihood of survival from which we infer the benefit of tier 1 care. The nominal survival probability can be estimated using the thermal injury mortality model (TIMM model) in Osler et al. (2010), which is based on a nonlinear function of patient's age, burn size, and presence of inhalation injury. This provides a continuous measure for mortality rate rather than the previously used coarse matrix blocks based on age and severity of burn, as in Saffle et al. (2005). More specifically, the TIMM model uses the following logistic regression model to predict the thermal injury probability of survival:

$$\begin{aligned} P_i = [1 + \exp(&\beta_0 + \beta_1 TBSA + \beta_2 Age + \beta_3 IHI \\ &+ \beta_4\sqrt{TBSA} + \beta_5\sqrt{Age} + \beta_6 TBSA \times IHI \\ &+ \beta_7 Age \times IHI + \beta_8 TBSA \times Age/100)]^{-1}, \end{aligned} \quad (4)$$

where $TBSA$ is measured in percentage, Age is measured in years, and IHI is a binary variable. The coefficients of the function are estimated from the National Burn Repository data set (39,888 patients) and are listed in Table 2. We assume that this survival probability decreases for patients who are admitted to a burn center after the initial three- or five-day window. This decrease captures the *benefit* of tier 1 burn care.

4.1.2. Benefit. There is no generally accepted model for how patients' conditions evolve over time depending on the type of treatment given. This is primarily because of the limited quantitative data on the reduction in mortality when transferred into a burn center. Sheridan et al. (1999) is one of the few works that looks at the impact of delayed transfers; however, the study only includes a total of 16 pediatric patients with delayed treatment of up to 44 days. The small sample size, the specialized population, and the often long delays involved make it impossible to use the Sheridan et al. (1999) results in our model. As such, we infer the benefit of burn center care based on the New York City plan and the judgment of the clinicians on the Task Force.

Table 2 TIMM Coefficients, as Reported in Osler et al. (2010)

k	Variable	β_k
0	Constant	−7.6388
1	*TBSA*	0.0368
2	*Age*	0.1360
3	*IHI*	3.3329
4	$\sqrt{TBSA}$	0.4839
5	$\sqrt{Age}$	−0.8158
6	$TBSA \times IHI$	−0.0262
7	$Age \times IHI$	−0.0222
8	$TBSA \times Age/100$	0.0236

To translate our objective into the increase in number of survivors, we introduce the following construct: Each patient has a deterioration factor $w \in [0, 1]$, which represents the *relative* benefit of tier 1 burn care; i.e., the patient's survivability will decrease by w if he is not transferred to a burn bed before his delay tolerance expires. A patient's *absolute* benefit is then

$$\Delta P_i = w_i P_i.$$

The deterioration factors are chosen so that, in general, priority is given to type 1 patients, followed by type 2 patients, and finally type 3 patients. This is to be consistent with the clinical judgment used to establish the initial triage matrix. In that spirit we assume that, within each patient type, the relative benefit of tier 1 treatment is identical. As such, we must derive four deterioration factors: w_1, w_{2A}, w_{2B}, and w_3. Because the survivability of patients within each type can vary quite a bit, the absolute benefit, ΔP_i, will differ across patients of the same type.

We start with an estimate of the range of w_{2A} and derive ranges for the remaining patient types. The survivability for type 2A patients is very high; hence, even a small deterioration factor translates into a large benefit. As such, and supported by clinical judgment, we assume this factor is between 5% and 15%. Because the absolute benefit for type 1 patients is assumed to be the largest (resulting in their initial priority for tier 1 treatment), we require that $w_1 > w_{2A}$. More generally, given w_{2A}, the ranges of deterioration factors for the other patient types are estimated so as to be consistent with the priorities given by the triage matrix in Figure 2. These deterioration factors and approximate survivability ranges are listed in Table 3. We see that there is a substantial range for each of the deterioration factors. The majority of our results below assumes $(w_1, w_{2A}, w_{2B}, w_3) = (0.5, 0.1, 0.4, 0.2)$; however, we do sensitivity analysis over the entire range of each parameter.

Because of a lack of data on the health evolution of burn patients and how it is affected by delay in treatment in burn units, the best estimates of survival benefit must be based on a combination of general survival data and clinical judgment. However, our methodology can readily be modified as more work is done to establish more sophisticated health evolution models. Such work would be very valuable in assessing alternative burn disaster response plans.

Table 3 Approximate Range of Survival Probability and Deterioration Weights for Different Types of Patients

Patient type	Type 1	Type 2A	Type 2B	Type 3
Survival probability: P_i	0.5–1.0	0.6–1.0	0.1–0.6	0–0.2
Deterioration weight: w_i	0.1–0.75	0.05–0.15	0.1–0.6	0.05–0.3

Table 4 Mean Patient Length of Stay and Standard Deviation for Burn-Injured Patients Grouped by Burn Size and Survival Outcome, as Summarized from the American Burn Association (2009)

	Burn severity in % TBSA									
Outcome	0.1–9.9	10–19.9	20–29.9	30–39.9	40–49.9	50–59.9	60–69.9	70–79.9	80–89.9	90+
All										
LOS, days	5.4	12.0	21.5	32.6	40.4	42.5	45.1	39.5	35.3	19.5
Std. dev.	10.0	13.3	21.2	28.0	35.7	40.9	49.0	55.0	62.1	54.2
Lived										
LOS, days	5.4	11.7	21.7	34.8	47.7	56.7	66.5	75.8	88.9	65.6
Std. dev.	10.0	13.1	20.3	27.2	35.4	39.8	50.1	62.6	84.3	99.2
Dead										
LOS, days	16.6	21.8	19.7	20.6	18.1	17.3	16.7	12.7	11.5	8.6
Std. dev.	22.9	25.5	25.4	30.1	26.1	29.1	29.3	25.8	24.0	27.3

4.1.3. Length of Stay. There currently does not exist a continuous model to predict mean LOS; however, once one becomes available, the proposed algorithm can easily be adapted to incorporate it. In the meantime, we utilize a discontinuous model where LOS is determined by the extent of the burn, as measured by TBSA. TBSA is the most critical factor in determining LOS. Skin-grafting surgeries that transplant healthy skin cells are limited in the area that can be treated in each surgery; therefore, larger TBSA tends to correspond with more surgeries and longer LOS for patients who survived. The expected LOS of a patient (L_i) is given by the mean LOS in the American Burn Association (2009), based on patient's TBSA and survival outcome, as summarized in Table 4.

4.1.4. Class. A patient's class, C_i, reflects his delay tolerance. This tolerance is determined based on the clinical judgment of the experienced burn clinicians. Recall that patients who are not treated within five days of burn injury are susceptible to infection and clinical complications. Such complications can arise earlier, by day 3, in more severe patients. We can refer to these patients as being less "delay tolerant," and therefore we assume that these patients must be transferred within three days to earn a reward. Clinical factors indicate that type 1 patients fall into this category and are defined as class 1 patients. Because type 2B and type 3 patients have more extensive burns and/or are older than type 1 patients, we expect them to be just as delay sensitive as the type 1 patients and are also classified as class 1. However, type 2A patients are better able to withstand transfer delays and therefore are classified as class 2 and generate a reward up to day 5. Because the first 72 hours are typically devoted to stabilizing the patient, we assume that the benefit of tier 1 treatment is invariant to the timing of admission as long as it falls within the relevant deadline.

Our proposed algorithm prioritizes patients in decreasing order of the ratio between benefit and probability of LOS less than three days ($\Delta P_i e^{3/L_i}$). In this case, patient i's benefit is the increase in likelihood of survival based on timely tier 1 care, $w_i P_i$, where P_i is given by the TIMM model (4); his expected LOS, L_i, is given by Table 4; and his delay tolerance class, C_i, depends on his triage tier given by Figure 2. Table 5 summarizes how these parameters are assigned.

Table 5 Summary of How Model Parameters Are Assigned to Patients

	Patient type			
Parameter	Type 1	Type 2A	Type 2B	Type 3
Class: C_i	1	2	1	1
Mean LOS: L_i	NBR data in Table 4			
Survival probability: P_i	TIMM model (4)			
Deterioration weight: w_i	0.5	0.1	0.4	0.2
Benefit: ΔP_i	$w_i P_i$			

Notes. Deterioration weights w_i are listed as the values used for most results. Ranges for these values can be found in Table 3.

4.2. Inclusion of Patient Comorbidities

Thus far, the triage score assumes that there is no information regarding patient comorbidities. Thombs et al. (2007) demonstrated that certain comorbidities can significantly affect a patient's survival probability and LOS. In a more recent paper, Osler et al. (2011) developed a regression model for estimating survival probabilities that incorporates comorbidities. However, the Osler et al. (2011) model was based on a more limited database from New York State that included patients who were treated in non–burn units. Therefore, we used the results in Thombs et al. (2007) to consider the impact of including specific patient comorbidities. More precisely, if patient i has comorbidity j with associated odds ratio, OR_j, and transform coefficient, TC_j,[1] then his probability of

[1] A transform coefficient is a multiplier that increases LOS by a proportional amount, TC_j.

survival and LOS are adjusted from the base values if he did not have comorbidity j:

$$P_i^Y = \frac{P_i^N}{P_i^N + (1-P_i^N)OR_j}, \qquad L_i^Y = TC_j L_i^N, \tag{5}$$

where the superscript denotes whether the patient has the comorbidity: Y for yes and N for no. Note that the TIMM model and LOS estimates include patients with comorbidities. Hence, those estimates can be used to determine P_i^N and L_i^N based on the prevalence, q_j, of comorbidity j in the sample used for estimation:

$$\begin{aligned} E[P_i] &= (1-q_j)P_i^N + q_j P_i^Y \\ &= (1-q_j)P_i^N + q_j \frac{P_i^N}{P_i^N + (1-P_i^N)OR_j}, \\ E[L_i] &= (1-q_j)L_i^N + q_j L_i^Y = (1-q_j)L_i^N + q_j TC_j L_i^N. \end{aligned} \tag{6}$$

Table 6 summarizes the odds ratios and transform coefficients for the comorbidities that have statistically significant impact on mortality and/or LOS. It also includes the prevalence in the National Burn Repository data set, which was used to estimate these parameters and was required to determine P_i^N and L_i^N.

Thombs et al. (2007) determined that if a patient has more than one comorbidity, then his survival probability is first adjusted by the most significant (in terms of impact) comorbidity, and is further adjusted by each additional (but no more than three) comorbidities using an odds ratio of 1.33. For example, consider a 50-year-old patient with TBSA = 11% and no inhalation injury; hence, he is type 2A. This patient has renal disease and is obese. Based on his age, TBSA, and lack of inhalation injury, his nominal survival probability and expected LOS are $P_i^N = 0.918$ and $L_i^N = 13.6$ days. His deterioration factor is $w_{2A} = 0.1$. Now, we adjust for the comorbidities: first adjusting for renal disease and then adjusting with an odds ratio of 1.33 for additionally being obese:

$$\begin{aligned} P_i^Y &= \frac{P_i^N}{P_i^N + (1-P_i^N)\cdot 5.11} \\ &\quad \cdot \left(\frac{P_i^N}{P_i^N + (1-P_i^N)\cdot 5.11} + \left(1 - \frac{P_i^N}{P_i^N + (1-P_i^N)\cdot 5.11}\right)\cdot 1.33 \right)^{-1} \\ &= 0.622 \\ L_i^Y &= 1.44 L_i^N = 19.6 \text{ days}. \end{aligned} \tag{7}$$

We can see that this patient's comorbidities significantly alters his triage priority index from $\Delta P_i e^{3/L_i} = 0.1145$ to $\Delta P_i^A e^{3/L_i^A} = 0.07249$. Depending on the demographics of the other patients, this change could be the difference between being transferred first or last.

Table 6 Odds Ratio (OR), Transform Coefficient (TC), and Prevalence of Various Comorbidities, as Reported in Thombs et al. (2007) and Others

Comorbidity category	OR	TC	Prevalence (%) NBR	NYC	US
HIV/AIDS	10.19	1.49	0.2	0.46	0.37
Renal disease	5.11	1.44	0.6		16.8
Liver disease	4.82	1.3	0.6	2	
Metastatic cancer	4.55	NS	0.6		0.447
Pulmonary circulation disorders	2.88	NS	0.1		< 3
Congestive heart failure	2.39	1.23	1.6		1.76
Obesity	2.11	NS	1.2	25.6	33.8
Malignancy without metastasis	2.08	NS	0.4		0.447
Peripheral vascular disorders	1.84	1.39	0.6		5 | 50+
Alcohol abuse	1.83	1.36	5.8	4.65	4.3
Other neurological disorders	1.56	1.52	1.6		< 2
Cardiac arrhythmias	1.49	1.4	2.0		12.6 | 60+
Cerebrovascular disease	NS	1.14	0.3		< 2
Dementia	NS	1.6	0.3		13.9 | 70+
Diabetes	NS	1.26	4.4	12.5	7.8
Drug abuse	NS	1.2	3.3	16	14
Hypertension	NS	1.17	9.6	28.8	21.7
Paralysis	NS	1.9	1.7		1.9
Peptic ulcer disease	NS	1.53	0.4		< 1
Psychiatric diagnosis	NS	1.42	2.9		< 1
Valvular disease	NS	1.32	0.4		< 2

Notes. Prevalence is given for the American Burn Association–National Burn Repository (ABA-NBR), whereas for New York City and the United States, it is given for the general population. When it is specified by age, the age group is listed after the separation bar, i.e., the prevalence for peripheral vascular disorder is given for people aged 50 and older. Sources for prevalence information can be found in Appendix D.

4.3. Summary of Proposed Triage Algorithm

The triage algorithm can be summarized as follows:

1. For each patient, i, determine his triage type, survivability, P_i^A, and expected LOS, L_i^A. The superscript A denotes the fact that these parameters are adjusted if it is known whether the patient has or does not have a significant comorbidity.
2. Patient i's benefit is $\Delta P_i = w_i P_i^A$; his deterioration factor is $w_i = 0.5$ if patient i is type 1, $w_i = 0.1$ if he is type 2A, $w_i = 0.4$ if he is type 2B, and $w_i = 0.2$ if he is type 3; his class is $C_i = 2$ if patient i is type 2A, otherwise $C_i = 1$.
3. Prioritize patients based on their triage index: $\Delta P_i e^{3/L_i^A}$.
4. Patient i generates reward $\Delta P_i[\mathbf{1}_{\{t_i \le 3,\, C_i=1\}} + \mathbf{1}_{\{t_i \le 5,\, C_i=2\}}]$, where t_i is the time at which he is transferred into a tier 1 burn bed.

Note that the presented algorithm serves as the baseline for patient prioritization, and clinical judgment can be used to reduce a patient's prioritization in special circumstances, such as family wishes for limited end-of-life care, presence of an imminently terminal illness, and/or a Glasgow Coma Score of less than 6, which reflects severe brain injury and low cognitive activity.

5. Evaluating the Algorithm

We now evaluate our proposed algorithm relative to four others using simulation. The first algorithm, referred to as the original algorithm, is the original three-tier triage matrix proposed in Yurt et al. (2008) and depicted in Figure 2. Because there is no differentiation within each tier, the algorithm is equivalent to randomly prioritizing patients within each tier. The second algorithm, referred to as the survival algorithm, follows the initial proposal of the Task Force, which is to differentiate patients within a single triage tier based only on survival probability. The remaining algorithms utilize the parameters whose estimation is given in §4.1. The third algorithm is weighted shortest processing time first. The fourth algorithm, referred to as the proposed-N algorithm, is our proposed algorithm, but assumes that *no* information about comorbidities is known. The fifth algorithm is our proposed-W algorithm *with* comorbidities, i.e., it accounts for the presence (or lack) of comorbidities and ranks patients based on their *adjusted* index. We use simulation to estimate expected rewards. Details of our simulation model can be found in Appendix A. Table 7 summarizes the algorithms that are simulated.

5.1. Data Description

In this section, we describe the patient data that we use in our simulation model to compare the triage algorithms described in the previous section. We have a number of data sources: 775 cases of patients treated at the New York-Presbyterian/Weill Cornell Medical Center Burn Center during the year 2009, published data from previous disaster events, and published census data. The patient population from NY-Presbyterian (NYP) is generally not indicative of what would be expected in a disaster scenario—for example, nearly 50% of the patients are under the age of five and the median TBSA was 2%. Given that age is a significant factor in determining patient survivability and LOS, we turn to published data on previous disaster events to build representative scenarios of the types for which the Federal Health Resources and Services Administration wants to prepare. We will return to the NYP data when considering the feasibility of the federal mandate in §6.

Table 7 **Triage Index**

Triage algorithm	Index
Original (from Yurt et al. 2008)	Tiered with random selection
Survival	Tiered with priority in each tier according to P_i
WSPT	$\Delta P_i / L_i^A$
Proposed-N	$\Delta P_i e^{3/L_i}$
Proposed-W	$\Delta P_i e^{3/L_i^A}$

Note. Higher index corresponds to higher priority for a tier 1 bed.

Table 8 **Distribution of Age, Severity of Burn (TBSA), and Inhalation Injury (When Known) in Burn Data, as Summarized from Yurt et al. (2005), Chim et al. (2007), and Mahoney et al. (2005)**

	Age			TBSA (%)			
Event	Median	Min.	Max.	Median	Min.	Max.	IHI (%)
9/11	44 (avg.)	27	59	52 (avg.)	14	100	66.7
Bali 2002	29	20	50	29	5	55	
Jakarta 2003	35	24	56	10	2	46	
Rhode Island 2005	31 (avg.)	18	43	<20	<20	>40	

Each simulation scenario we consider attempts to emulate the demographics and severity of prior burn disasters. We looked at four disaster events: the NYC World Trade Center attacks on September 11, 2001 (9/11) (Yurt et al. 2005), a 2002 suicide bombing in Bali (Chim et al. 2007), a 2003 suicide bombing at the Jakarta Marriot hotel (Chim et al. 2007), and a 2003 nightclub fire in Rhode Island (Mahoney et al. 2005). The patients' ages ranged from 18 to 59, and the severity of burns ranged from 2% to 100% TBSA. These statistics are summarized in Table 8. The patients in the four disaster events were older and experienced more severe burns than the average patient treated at NYP in 2009.

Besides the 9/11 event, there was no information on patient inhalation injury. However, the data from the National Burn Repository (NBR) does include this information for burn-injured patients treated from 1973 to 2007. We have summarized the distribution of IHI based on age and extent of burn in Table B.1 in Appendix B. The average IHI across patients in the NBR data who fall within the same demographics as 9/11—i.e., age from $[30, 60]$ and TBSA from $[20\%, 100\%]$—is 48.95%, which is slightly lower than the observed 66.7% documented from 9/11.

There was no information on the presence of comorbidities in these references. We used a series of references to collect prevalence data of relevant comorbidities in the general population. Prevalence of any given comorbidity could be dependent on the type of event as well as where it takes place. The population in an office building may have a different set of demographics than that in a subway or sports arena. Therefore, it would be desirable to have prevalence data based on, at the very least, age and gender. However, this fine-grained information was not generally available; therefore, for consistency, we used prevalence for the general population. In some cases, we were able to get prevalence data specific to NYC or New York State rather than national data. Because these data more closely correspond to the potential burn-injured patient population for which the algorithm was being developed, we used these when available. The prevalence of the comorbidities of interest are summarized in Table 6.

Table 9 **Distribution of Age, Severity of Burn (TBSA), and Inhalation Injury for Four Simulation Scenarios**

	Age	TBSA (%)	IHI
Scenario	Uniform distribution	Uniform distribution	Bernoulli distribution
1	[18, 60]	[0, 60]	0.667
2	[18, 60]	[0, 60]	NBR data in Table B.1
3	[18, 60]	[10, 90]	0.667
4	[18, 60]	[10, 90]	NBR data in Table B.1

5.2. Simulation Scenarios

Because of the variability across the burn disaster events, we consider a number of simulation scenarios. We simulate the average increase in number of survivors due to tier 1 treatment for the triage policies described above.

For the sake of simplicity, our simulations assume that all burn beds are available to handle the burn victims resulting from the catastrophe. We discuss the implications of this assumption later. The number of burn beds is fixed at 210 to represent the total number of tier 1 beds in the NYC region when accounting for the surge capacity. We consider scenarios that are likely to be representative of an actual burn disaster. The first scenario is based on the Indonesia and Rhode Island events. Age is uniformly distributed from [18, 60], burn severity is uniformly distributed from [0%, 60%], and inhalation injury is present with probability that is consistent with 9/11, i.e., 0.667. For our second scenario, we consider inhalation injury that is dependent on age and TBSA as summarized in Table B.1. Our third and fourth scenarios aim to be representative of events like 9/11: the age distribution is still [18, 60], but the extent of the burn is more severe, with TBSA uniformly distributed from [10%, 90%]. In summary, the four scenarios we consider are listed in Table 9, and Table 10 shows the statistics of patients in terms of class and type under each scenario.

5.3. Simulation Results: Unknown Comorbidities

We compare the relative improvement in benefit under four different triage algorithms described in Table 7. Hence, the performance is given by the increase in average number of survivors due to timely transfer into tier 1 beds within the three- to five-day window divided by the number of survivors under the original block triage system. We assume that comorbidities are unknown or ignored. Hence, in this case $P_i^A = P_i$

Table 10 **Scenario Statistics**

Scenario	Class 1 (%)	Class 2 (%)	Type 1 (%)	Type 2 or 3 (%)
1	93.9	6.1	85.5	14.4
2	81.7	18.3	74.2	25.8
3	95.9	4.1	58.7	41.3
4	88.8	11.3	54.5	45.4

and $L_i^A = L_i$, so that the proposed-N and proposed-W algorithms are identical. Figure 3 shows the relative improvement of the objective compared to the original triage algorithm from Yurt et al. (2008).

It is clear that the impact of including LOS in the triage score depends on the type of event as given by the age and severity of the burn victims. In severe cases (scenarios 3 and 4), ignoring LOS and simply using survivability (survival algorithm: P_0) does noticeably worse than the proposed-N algorithm. The proposed-N algorithm *always* outperforms the original algorithm, by as much as 10%, which corresponds to 21 additional lives saved. In some cases, WSPT generates more than 5% less benefit than the original algorithm; this is expected because, as discussed in §3.1, WSPT is suboptimal.

5.4. Simulation Results: Comorbidities

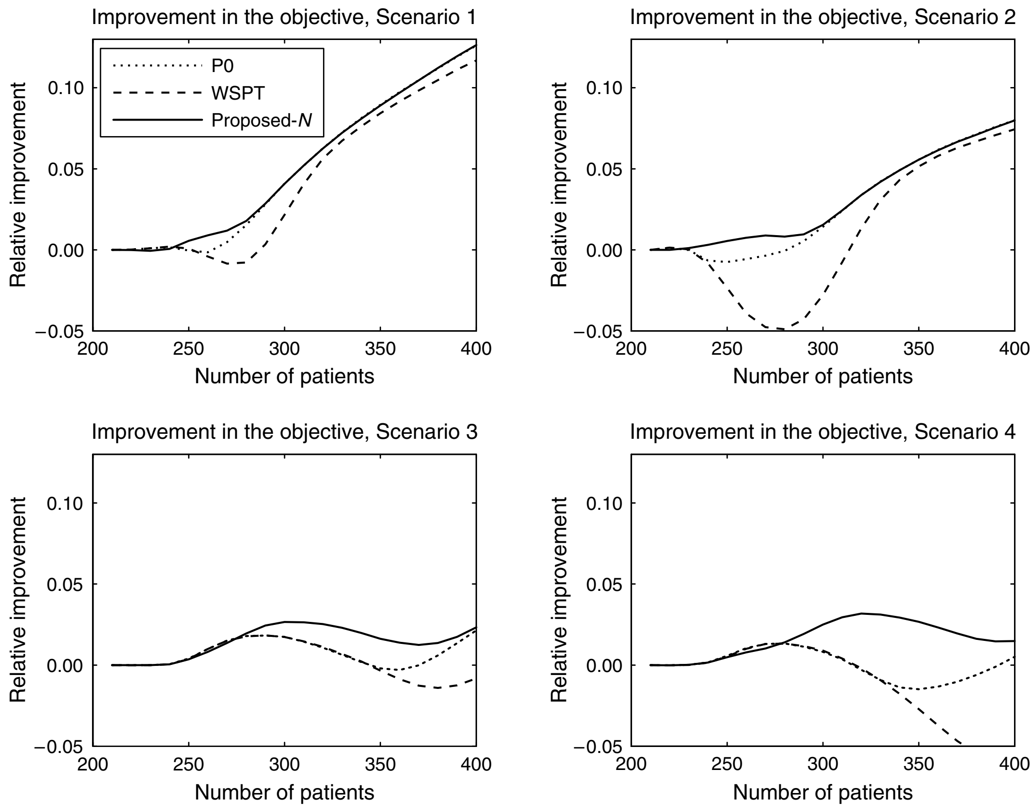
We now consider the impact of incorporating comorbidities in triaging patients. Determining the presence of comorbidities may be costly or difficult. This determination has to be made within the first hours and certainly within the first day as triage decisions are made. Some comorbidities, such as obesity, can easily be determined upon simple examination, whereas others, such as HIV, may be less so. Although some comorbidities will show up via routine blood work done upon arrival at the hospital, the laboratory may be overwhelmed in a disaster scenario, causing delays in obtaining these results. Additionally, some patients may arrive at the hospital unconscious or they may be intubated immediately upon arrival to the hospital, making it difficult or impossible for them to communicate which comorbidities they have. As information about comorbidities becomes available, they can be used to transfer patients to the correct tier.

The NYC Task Force was hesitant to incorporate comorbidities into the triage algorithm because of potential difficulties in identifying the presence of comorbidities. However, as seen in Thombs et al. (2007), the presence of comorbidities can significantly affect mortality and LOS, which will ultimately affect a patient's triage priority. Uncertainty about the presence of a comorbidity may result in an incorrect triage priority, ultimately resulting in a reduction in total average benefit generated by the triage algorithm. On the other hand, the impact of some comorbidities may be so limited that knowledge of them would not significantly affect the expected benefit. Therefore, it is important to determine which comorbidities are likely to be worth the cost of identifying for use in triage.

For each comorbidity, j, with associated odds ratio OR_j, transform coefficient TC_j, and prevalence q_j, consider the following two extreme scenarios:

1. Perfect information of comorbidity j is available. That is, we know whether each patient does

Figure 3 **Relative Improvement of Average Additional Survivors**



or does not have comorbidity j, in which case we can adjust the survival probability and LOS accordingly as described in (5). That is, if the patient has the comorbidity, $P_i^A = P_i^Y$ and $L_i^A = L_i^Y$, else $P_i^A = P_i^N$ and $L_i^A = L_i^N$.

2. No information of comorbidity j is available. We assume each patient has comorbidity j with probability q_j, where q_j is the prevalence of comorbidity j in the population. The expectation of the adjusted probability and probability of completing within three days are

$$P_i^A = q_j P_i^Y + (1-q_j)P_i^N,$$
$$E[P(S_i < 3)] = E[e^{3/L_i^A}] = q_j e^{3/L_i^Y} + (1-q_j)e^{3/L_i^N}, \tag{8}$$

where P_i^N and L_i^N are the nominal survival probability and LOS, respectively, given that patient i has no comorbidities. Patient i's index is then given by $\Delta P_i E[e^{3/L_i^A}]$, with $\Delta P_i = w_i P_i^A$.

For each comorbidity, we compare the average additional number of survivors due to burn bed treatment in each scenario. In particular, we examine the relative improvement of having perfect information for comorbidity j versus having no information. Again, we consider the four scenarios based on the previous disaster events. Because these references do not have information regarding comorbidities, we randomly generated comorbidities for each patient based on the available prevalence data in Table 6. We generated 10,000 patient cohorts and corresponding realizations of LOS, survival, inhalation injury, and (non) existence of comorbidity j.

The comorbidities with significant impact are summarized in Table 11. The comorbidities that are omitted have no significant impact due to the small effect on LOS or survival and/or due to low prevalence. In all scenarios, renal disease has the most significant improvement for having full information versus no information with relative improvement 1.381%–1.578%. The relative improvement for all remaining comorbidities is less than 0.5%—more than a factor of two less than renal disease. We note that in this case, renal disease includes varying levels of disease severity and is defined by 13 different ICD9 codes, one of which corresponds to end-stage renal disease. Recognizing that highly complex algorithms that require a lot of information gathering and training will be difficult to implement during disaster scenarios, we elect to include only one comorbidity in the final triage algorithm: renal disease.

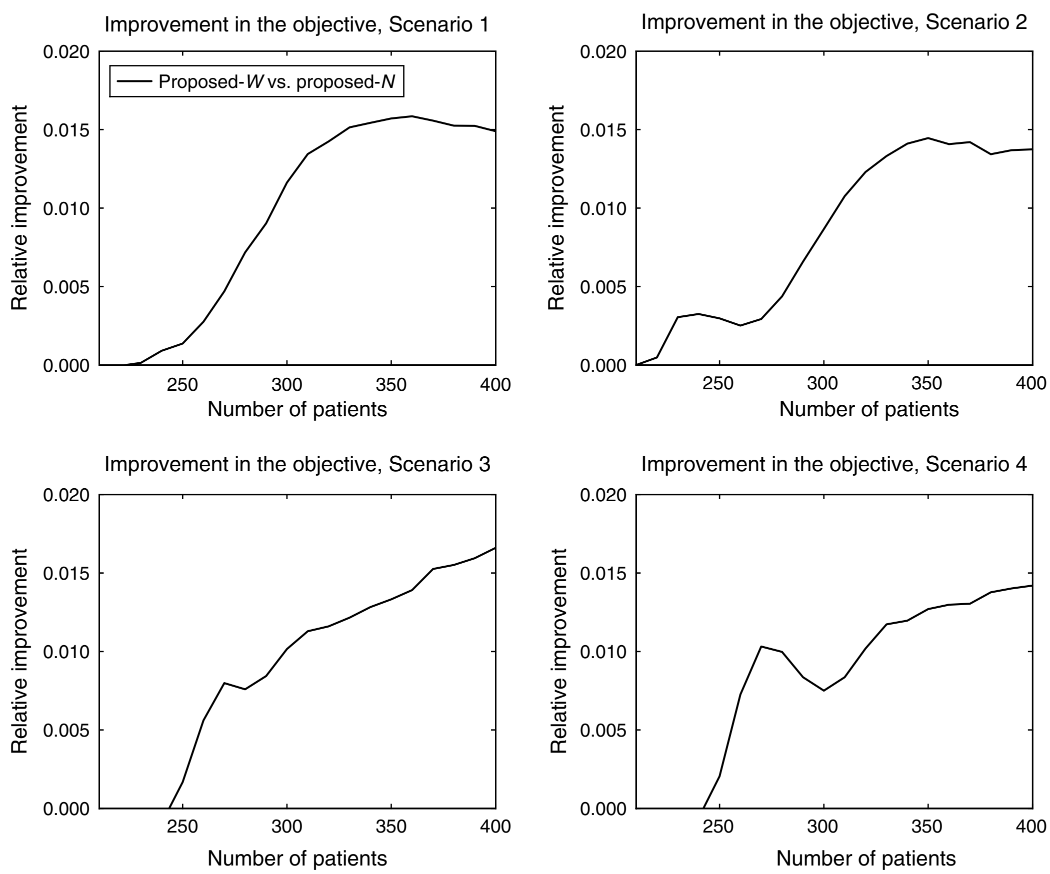
5.5. Performance of the Proposed Triage Algorithm

The final triage algorithm we propose prioritizes patients based on the index that is the ratio of their benefit in probability of survival from treatment in a

Table 11 Impact of Comorbidity Information: Relative Improvement and Standard Error in Percentages

	Relative improvement (std. err.)			
Comorbidity category	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Renal disease	1.534 (0.036)	1.486 (0.038)	1.578 (0.043)	1.381 (0.040)
Obesity	0.332 (0.029)	0.356 (0.030)	0.402 (0.033)	0.332 (0.033)
Liver disease	0.288 (0.017)	0.313 (0.018)	0.335 (0.020)	0.277 (0.018)
HIV/AIDS	0.119 (0.008)	0.108 (0.009)	0.109 (0.010)	0.090 (0.009)
Pulmonary circulation disorders	0.101 (0.013)	0.108 (0.014)	0.134 (0.016)	0.117 (0.015)
Alcohol abuse	0.087 (0.013)	0.095 (0.014)	0.109 (0.016)	0.082 (0.015)
Congestive heart failure	0.074 (0.010)	0.061 (0.011)	0.071 (0.012)	0.047 (0.011)
Metastatic cancer	0.045 (0.007)	0.033 (0.007)	0.052 (0.008)	0.047 (0.007)
Peripheral vascular disorders	0.028 (0.007)	0.025 (0.007)	0.031 (0.008)	0.041 (0.007)

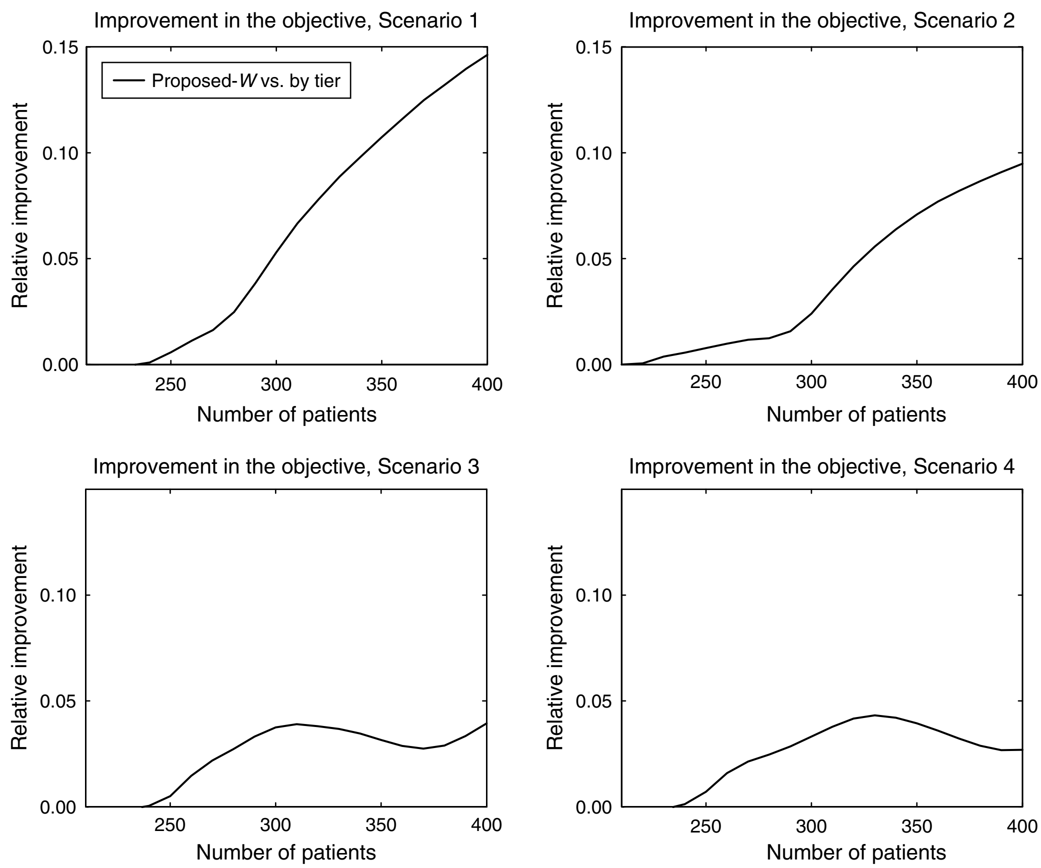
Figure 4 Relative Improvement of Average Increase in Number of Survivors Due to Tier 1 Treatment: Proposed-*W* vs. Proposed-*N*



burn bed to their adjusted probability of completing treatment within three days: $\Delta P_i^A e^{3/L_i^A}$. A patient's LOS and benefit are adjusted if the patient has renal disease, but ignores all other comorbidities. In our simulations, we assume full knowledge of renal disease because this may be detected through routine blood tests.[2] In more extreme cases of renal disease, such as chronic, end-stage renal disease requiring dialysis, a physical exam that reveals an implanted dialysis catheter can reveal such a condition. Using our simulation model described in Appendix A, we compare the performance in terms of average increase in number of survivors due to burn bed treatment of the proposed-*W* triage algorithm to the proposed-*N* algorithm (Figure 4) and to the original one that was proposed in Yurt et al. (2008) (Figure 5), which do not utilize comorbidity information to adjust a patient's probability of survival and expected LOS. In all scenarios, the proposed-*W* algorithm achieves over 1.5% more reward (3 additional lives saved) than the

[2] We note that other insults to the renal system that may result from acute burn trauma or resuscitation process can mimic these findings.

Figure 5 **Relative Improvement of Average Increase in Number of Survivors Due to Tier 1 Treatment: Proposed-*W* vs. Original**



proposed-*N* algorithm and 2.5% more reward than the original algorithm. In scenario 1, proposed-*W* achieves up to 15% more reward (31 additional lives saved).

Under severe disaster scenarios (scenarios 3 and 4), the relative benefit is much lower. This is because in severe events, the number of survivors is going to be quite low, irrespective of the algorithm used. Additionally, there is low bed turnover (only 7–12 additional patients are admitted from the tier 2/3 hospitals within three to five days as compared to up to 36 additional patients under scenario 1), so all algorithms are unable to provide treatment in burn units for many patients beyond the initial 210 that are admitted. However, we note that in such cases, accounting for LOS is even more essential because any sort of turnover will be helpful (refer back to Figure 3 to see the benefits of including LOS). Although prioritizing solely based on survivability performs reasonably well, we emphasize that the proposed-*W* algorithm still outperforms the others.

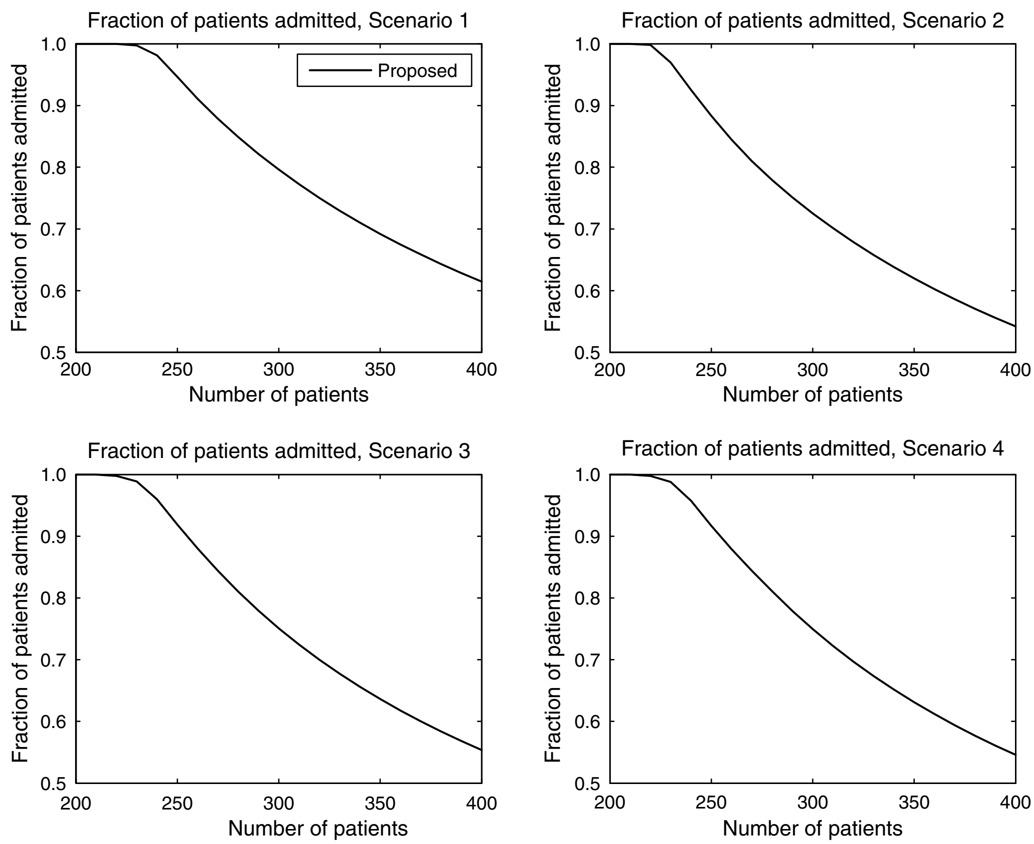
It is also interesting to consider the variation in the number of survivors under each triage algorithm. Although we notice that the proposed-*W* policy outperforms all other policies with respect to expected number of survivors, this could potentially come with increased variation, i.e., risk. When comparing the standard deviation of the number of survivors in our simulations, we find that the proposed-*W* policy always has the smallest standard deviation. Hence, we find that our proposed algorithm not only yields a higher expected number of survivors but also a slightly lower level of uncertainty.

We note that the results were similar over various values of the deterioration factors within the allowable ranges specified in Table 3. In all cases, proposed-*W* outperformed all of the other policies. The magnitude of this improvement varied from 2.2% to 16.1%.

6. Feasibility

In this section, we analyze the feasibility of admitting all eligible burn-injured patients to a burn center during the specified time frame during a catastrophe given the current burn bed capacity and the proposed burn disaster plan. With a surge capacity of 210 burn beds in the NYC region, all patients can be immediately cared for in a tier 1 bed if there are 210 or fewer patients. However, as can be seen in Table 4, burn-injured patients can have long recovery times—much longer than five days—and so it is not at all clear that the requisite 400 patients can all be transferred to a burn bed during the three- to five-day time period.

Figure 6 Feasibility: Number of Beds Fixed at 210



The feasibility of meeting the government mandate will be highly dependent on the size of the event, i.e., the number of patients, as well as the severity of the patients. If most patients have minimal burns (i.e., TBSA $< 10\%$), they will have shorter LOS; there will be more turnover in the tier 1 burn beds; and more patients can be cared for in the first few days following the event. On the other hand, if most patients have very severe burns, they will have very long LOS, and it is unlikely that many new patients will be transferred within the specified time frame.

We consider the four scenarios for events as summarized in Table 9. The number of tier 1 beds is fixed at 210, and we vary the number of patients in the event. For all of our simulations, we use the proposed-W triage algorithm, which includes information about renal disease and prioritizes patients according to their score: $\Delta P_i e^{3/L_i^A}$. Figure 6 shows the percentage of admitted patients. With more than 250 patients, some patients cannot be transferred within the specified three- to five-day window. In events with more severe patients (scenarios 3 and 4), more than 45% of the 400 patients cannot be transferred within the desired time frame.

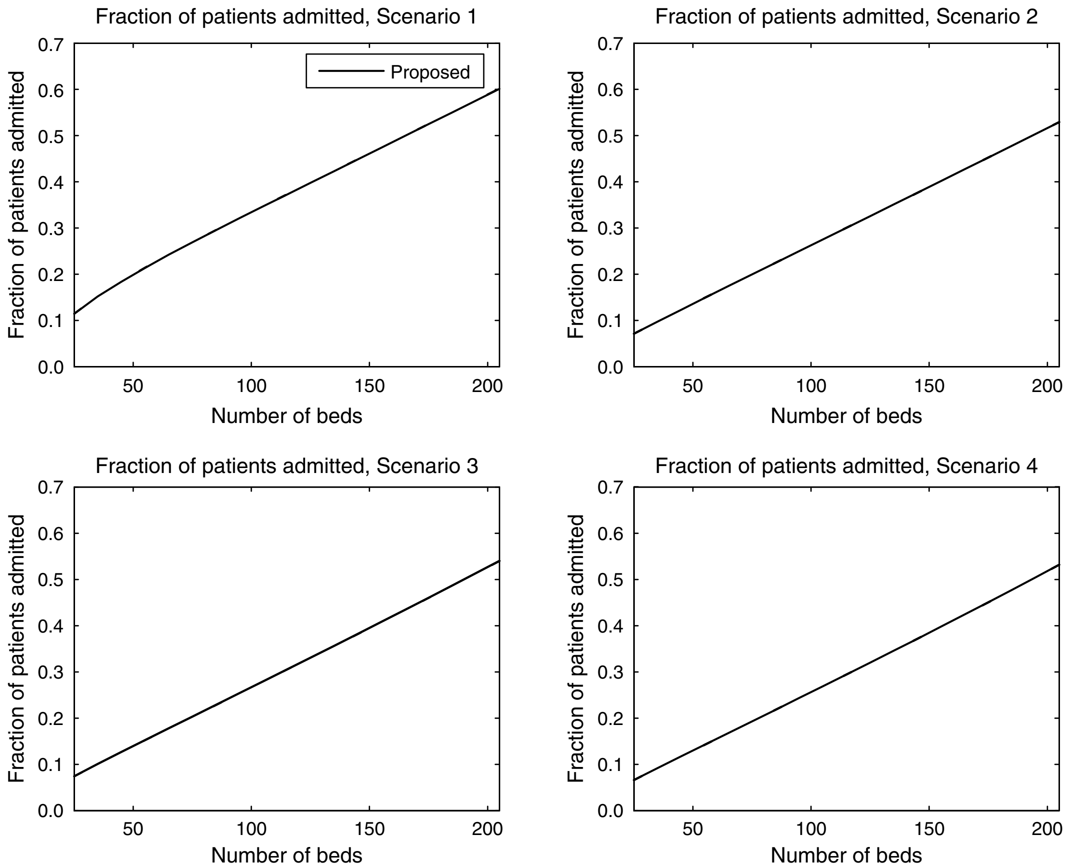
6.1. Clearing Current Patients

In assessing the feasibility of meeting the government mandate, we assumed that the burn centers could be cleared of all current patients in order to accommodate new patients from the burn disaster. On September 11, 2001, NYP was able to transfer all current patients to make room for all new burn-injured patients (Yurt et al. 2005). However, there were only 41 burn-injured patients who were directly admitted or transferred into a burn center, which is substantially smaller than the 400 required by the federal government.

NYP has one of the largest burn centers in the country with 40 beds. We obtained data on all patients who were treated in this center during 2009, including patient age, burn severity as measured by TBSA, presence of inhalation injury, gender, LOS, and comorbidity information. Although the patient population and severity of these 775 patients is quite different than prior burn disasters, we can utilize this data to consider the likelihood of clearing all patients if a disaster occurs.

In 2009, the average daily arrival rate was 2.12 per day, with a standard deviation of 1.56. Daily arrivals ranged from zero to seven. Figure C.1 in Appendix C shows the monthly and day-of-week patterns of daily arrivals. There was a peak in arrivals from January to April, which is consistent with anecdotal evidence from the burn clinicians, because burns are much more common in the winter months. Differences in

Figure 7 **Feasibility: Number of Patients Fixed at 400**



arrival rate across days of the week are not significant, although the number of admissions on Tuesdays is slightly higher. More importantly, the burn specialists at the NYP burn center estimate that the burn center is overcrowded on the order of twice a week during winter months. Hence, the number of beds that are available to care for burn disaster patients is likely to vary significantly depending on when the event takes place. Some current patients may be too severely injured to move out of the burn center, effectively removing beds from the disaster plan. The assumption of being able to clear all current patients is highly optimistic, making the feasibility of transferring all patients even more unlikely.

Given the possibility of having fewer than the maximum 210 beds, we consider how much more difficult it is to satisfy the federal mandate when fewer beds are available. Specifically, we assume there are 400 burn-injured patients, as given by the federal mandate, and consider the percentage of patients who are admitted within their deadline of three or five days, as appropriate. As seen in Figure 7, for a wide range of scenarios, it is likely that fewer than 200 patients (i.e., $<50\%$) will be able to receive tier 1 care within the desired time frame.

Clearly, the NYC disaster plan cannot meet the guidelines of the Federal Health Resources and Services Administration. To treat 50 burn-injured patients per million in population in NYC, more resources would be needed. Either more actual burn beds with the corresponding surgical facilities and professional staff capabilities would need to be provided or federal support to transport patients to burn centers in other states would be necessary to care for all 400 burn-injured patients. The amount of additional resources needed would vary depending on the type and size of event.

7. Conclusions and Discussion

Hospital systems and governments must be prepared to handle potential disaster events where the number of patients who seek care exceeds the initial available resources. Federal guidelines specify that metropolitan areas be able to care for 50 burn-injured patients per million in the three to five days following such an event. In this paper, we presented a triage system to maximize the expected benefit and applied it to evaluate the feasibility of meeting this standard given the mix of burn trauma beds and non–burn trauma beds that have been designated for use during a burn disaster in New York City. This triage algorithm is the first to incorporate burn center LOS and comorbidities to prioritize patients for transfer to burn beds.

Given the initial proposed NYC disaster plan, which utilizes burn beds in NYC and hospitals within a 60-mile radius region that have agreed to assist in an event, it is highly unlikely that all burn-injured patients will be able to be transferred into a tier 1 burn bed within five days. Moreover, ignoring patient LOS and some comorbidities would additionally reduce the total benefit to treated patients. These findings persuaded the NYC Task Force to incorporate these factors into their proposed revised triage plan. Leahy et al. (2012) described the current burn disaster plan recommendation by the NYC Task Force, including the triage plan described here, in addition to other considerations such as medical training for EMS and tier 2/3 personnel and provider indemnity.

Although we focus on burn disaster planning in NYC, the insights gained from this work can be applied to other cities. Because NYC is the largest city in the United States, it is often seen as a model for other metropolitan areas. In particular, it is clear that any triage system should incorporate LOS and some comorbidities such as renal disease. The need to explore methods to expand resources to satisfy the federal mandate depends on the current burn center resources and population. Certainly, NYC has the largest patient requirement, but it also has one of the largest (if not the largest) aggregate number of burn beds. There are only 125 burn centers in the United States (American Burn Association 2009), so although there are nine burn centers within a 60-mile radius of NYC, other cities may be more limited in the number of beds available at nearby burn centers. In situations where burn centers are available, these smaller cities are likely to be even more capacity constrained than NYC, making it even more essential to utilize a carefully designed triage algorithm.

One limitation of this work is that all of the available LOS data is based on scenarios where there is not a large backlog of patients waiting to be transferred into the burn center. Furthermore, the LOS from Saffle et al. (2005) is *hospital* LOS, not burn center LOS. However, these can be considered equivalent because most burn-injured patients are discharged directly from the burn center. In a catastrophic scenario, it may be possible to transfer burn-injured patients to non–burn beds before they are ready to be discharged from the hospital. This could free burn beds earlier, enabling additional patients to receive the necessary skin-grafting surgeries or wound care, thereby increasing the number of patients who are able to benefit from care in tier 1 beds. There is no available data regarding what the *minimal* LOS in the burn center would be; hence, we could not accurately account for this in our model. It may be possible to reduce LOS—a Canadian burn center was able to reduce patient LOS for patients with TBSA less than 20% and who did not require surgery (Jansen et al. 2012). However, the majority of patients in the disaster scenario considered in this paper are likely to require surgery and/or have TBSA greater than 20%, therefore it is not clear whether any significant reduction in LOS could be achieved in this situation.

Another limitation is that we have inferred the benefit of receiving treatment in a burn center within three to five days from the existing burn triage matrix. There is currently no quantitative data on the outcomes (survival or LOS) of burn-injured patients who are not treated in specialized burn centers, nor is there any evidence-based model of the impact of delay of surgery on mortality for patients in the first few days after injury. The only available information is qualitative and minimal—i.e., more sophisticated treatments, which are often performed in burn centers, have significantly improved LOS (Curreri et al. 1980)—or based on clinical judgement, as in Yurt et al. (2008). However, as more data become available, our methodology can be modified appropriately.

Finally, our triage model, as any other triage model, assumes accurate knowledge of the burn size and severity of each patient. However, anecdotal evidence (e.g., Lozano 2012) suggests that non–burn physicians often misjudge the extent of burns, resulting in both overestimates and underestimates. One possible remedy is the installation of high-resolution cameras in the tier 2/3 hospitals that would enable a burn specialist to make the assessments of TBSA for triage purposes. Such a program was successfully instituted at Lehigh Valley Health Network, Pennsylvania.

Despite these limitations, our work has improved upon the burn disaster plan initially developed by the NYC Task Force and described in Yurt et al. (2008). In particular, our proposed triage algorithm, which incorporates a continuous model for survival likelihood, patient LOS, and comorbidities, increases the number of survivors due to tier 1 treatment by up to 15%. Perhaps the most practically useful insight from this study is that the proposed tiered system may be sufficient in small to moderately sized events; however, the current resources are likely to be insufficient when the number of patients is large and/or the severity of burns is high. More generally, this demonstrates that non–burn beds that are used to stabilize patients awaiting care in a burn center have limited usefulness because of the long LOS of severely burned patients.

Appendix A. Simulation Model

We now describe the simulation model that is used to analyze various scenarios. This simulation model is based on the mathematical model described in §4 as well as discussions with burn physicians. There are currently 140 burn beds in

NYC and the surrounding area. These centers can be flexed up to 210 in a catastrophic event. We simulate a potential event in NYC and consider how patients are treated and transferred into these 210 tier 1 burn beds. The simulation considers a time period of five days, and makes the following assumptions:

(1) The number of beds is fixed at 210.

(2) All N patients are available to be transferred at the beginning of the horizon. These patients consist of inpatients only.

(3) Patient i has expected LOS, L_i. The realization of his LOS is independent of all other patients and is log-normally distributed with location and scale parameters calibrated using the mean and standard deviation from the National Burn Repository data as summarized in Table 4.

(4) Patient i is classified as class 1 ($C_i = 1$) if he is a type 1, 2B, or 3 patient. Otherwise, he is a type 2A patient (a tier 2/3 patient with TBSA less than 20% and no inhalation injury) and is classified as class 2 ($C_i = 2$).

(5) Patient i has benefit, $\Delta P_i = w_i P_i$, which is given by the TIMM model for survival probability, P_i, and the deterioration factor given in Table 3.

(a) If a class 1 patient is transferred into a burn bed within the first three days, he generates reward ΔP_i. Otherwise, he generates zero benefit.

(b) If a class 2 patient is transferred into a burn bed within the first five days, he generates reward ΔP_i. Otherwise, he generates zero benefit.

Patients are prioritized according to the specified triage algorithm. Patients who are not given a bed at the beginning of the horizon are assumed to be cared for and stabilized in a tier 2/3 hospital. Once a patient departs from the burn center, a new bed becomes available. The patient with the highest triage index is selected from the remaining patients to be transferred into the tier 1 burn bed. For each simulation, we generated 10,000 patient cohorts and realizations for LOS.

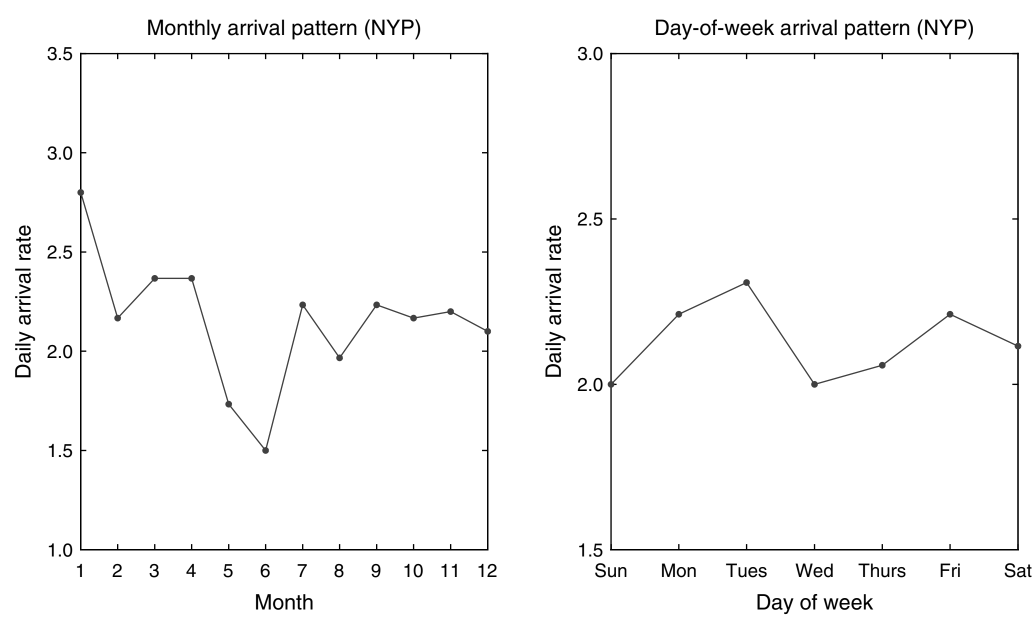
Appendix B. Inhalation Injury Summary

Table B.1 **Fraction of Patients with Inhalation Injury in the National Burn Repository Data Set, as Summarized from Osler et al. (2010)**

	Severity of burn: TBSA									
Age	0–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80	81–90	91–100
0–10	0.0077	0.0329	0.1053	0.2299	0.2526	0.2951	0.4000	0.6970	0.6190	0.6923
11–20	0.0174	0.0628	0.1300	0.1667	0.3333	0.2766	0.4211	0.4615	0.8500	0.6667
21–30	0.0332	0.0750	0.1859	0.3417	0.4493	0.5227	0.5263	0.5238	0.7692	0.6923
31–40	0.0360	0.0889	0.1672	0.3237	0.3768	0.4130	0.5833	0.4516	0.7826	0.6842
41–50	0.0450	0.1095	0.2436	0.3057	0.4719	0.4828	0.6471	0.5385	0.6000	0.5385
51–60	0.0563	0.1358	0.2523	0.3302	0.5417	0.5333	0.5385	0.6667	0.6087	0.6667
61–70	0.0772	0.1275	0.2168	0.3448	0.5926	0.6154	0.4444	0.5714	0.6250	0.7000
71–80	0.0779	0.1446	0.3137	0.3333	0.6129	0.4000	0.4444	0.7273	0.5000	1.0000
81–90	0.0722	0.1280	0.2364	0.4000	0.5000	0.5000	0.5833	0.6000	0.7000	1.0000
91–100	0.0620	0.0833	0.1111	0.6667	0.6667	1.0000	1.0000	0.0000	0.7500	—

Appendix C. Arrival Patterns of Burn-Injured Patients to New York-Presbyterian

Figure C.1 **Monthly and Day-of-Week Arrival Pattern in NYP Data Set**



Appendix D. Resources for Prevalence Data

Comorbiditiy	Resource
HIV/AIDS	Bloomberg and Frieden (2007)
Renal disease	Saydah et al. (2007)
Liver disease	New York City Department of Health and Mental Hygiene (2007)
Metastatic cancer	New York State Department of Health (2007)
Pulmonary circulation disorders	Tapson and Humbert (2006)
Congestive heart failure	New York State Department of Health (2000)
Obesity	Flegal et al. (2010)
Malignancy without metastasis	New York State Department of Health (2007)
Peripheral vascular disorders	Emedicine Health (2010)
Alcohol abuse	National Institute on Alcohol Abuse and Alcoholism (2004)
Other neurological disorders	Epilepsy Foundation (2010)
Cardiac arrhythmias	WrongDiagnosis (2011a)
Cerebrovascular disease	American Association of Neurological Surgeons (2005)
Dementia	New York State Department of Health (2004)
Diabetes	Thorpe et al. (2009)
Drug abuse	U.S. Department of Health and Human Services (2008)
Hypertension	New York City Department of Health and Mental Hygiene (2008)
Paralysis	WrongDiagnosis (2011b)
Peptic ulcer disease	WrongDiagnosis (2011c)
Valvular disease	Stewart et al. (1997)

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